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Final Technical Report
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DESIGN, DEVELOPMENT AND EVALUATION OF A DOUBLY ROTATED AK-CUT QUARTZ CRYSTAL

Frequency Electronics, Inc.

B. Goldfrank

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This report describes the work accomplished in designing, developing and evaluating a doubly rotated AK-cut quartz crystal. Standard production processes were used to fabricate AK-cut crystals with 0 = 36.48, 0 = 26.00 or 0 = 35.00 and 0 = 25.00. Frequency versus temperature characteristics, room temperature mode spectra and "G" sensitivity data were the main sources of data for evaluation. Crystals were fabricated at low frequencies and through subsequent lapping and polishing operations the frequencies were increased to determine a range of useful frequencies. Variations in shape, contour, blank size, electrode diameter and designed plateback were evaluated. Comparisons were made of "B" mode to "C" mode coupling and separation. unwanted mode suppression, angular rotation tolerances and "G" sensitivity. AK-cut lateral field resonators (AK-LFR) were also evaluated.

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Introduction.

The principal objective of this contract was the development of a doubly rotated (AK-cut) quartz crystal resonator. The resonator was to be characterized and optimized for turnover temperature, blank geometry, overtone operation, "B" to "C" mode coupling and separation, unwanted mode suppression, angular rotation tolerances and "G" sensitivity. Additionally, sufficient design information was to be obtained and presented to allow for ease of fabrication.

The primary advantage of the AK-cut is that there are large angle cutting tolerances. An error in cutting an AK crystal of ± 15 minutes in Ø or Θ does not affect the measured turnover temperature by more than ± 1°C near 80°C. In contrast, for an SC-cut crystal the equivalent tolerance is approximately ± 6 seconds, and for an AT-cut crystal the equivalent tolerance is approximately ± 15 seconds. This was the third contract under which the AK-cut was studied. Tables 1 and 2 show a summary of prior data taken on the fundamental mode for both the "C" and "B" modes (P.O.'s F19650-82-B-0578 and F19650-83-M-0713, respectively). For the present contract, we decided to confine our investigation to AK cut crystals with Ø = 36.58° and Θ = 26.00°. This angle was chosen for ease of x-raying, as a cross check to the cutting operations, and because of the theoretical turnover which is approximately 80°C. During the course of this study it was decided to also process crystals with a Ø = 35.00° and Θ = 25.00°. This decision was based on the desire to investigate

crystals that had similar performance to those crystals cut at ϕ = 36.00° and θ = 24.45°, where the fundamental and third overtone turnover temperature (T_{to}) are equal on the main mode. The theoretical T_{to} is also near 80° and would help confirm the shape of the theoretical isotherm previously referenced.

Various lots of crystals were processed. Typically starting at low fundamental frequencies and shallow curvatures, the blanks were processed and tested and then stripped, relapped and repolished to higher frequencies with, in some cases, an increase in curvature. Some crystals proved to be unmeasurable for any meaningful electrical responses, specifically the -1.75 diopter (plano-concave) and 0.00 diopter (plano-plano) crystals. These designs were quickly discarded. All other crystals were plano-convex. A complete summary of all frequencies, angles and contours studied is shown in Table 3.

Throughout the program difficulties were encountered in measuring the overtones. The third overtone has a multiplicity of anharmonic modes of varying strength[1,2] and the fifth overtone consistently had high resistance, which made measurements difficult.

1. A. Kahan and F.K. Euler, AK-Cut Quartz Resonators, J. Appl. Phys. 57(9), 4461 (1985).

2. A. Kahan, F.K. Euler, Proc. of 14th Precise Time and Time Interval (PTTI) Application and Planning Meeting NASA Conf. Publ. 2265, 1982, p. 577.

Prior work on SC-Cut crystals, which also have strongly coupled "B" modes showed that SC-cut blanks fabricated as lateral field resonator (LFR's)[3,4] were found to have superior performance and the "B" mode was completely eliminated. In a transverse mode resonator, the electric field is applied normal to the crystal thickness, whereas in the lateral field configuration the electric field is parallel to the major surfaces. As a final comparison of designs, we decided to fabricate some AK crystals as lateral field crystals. These crystals were designated AK-LFR'S. This effort was directed toward reducing the unwanted modes and thus improving the AK resonator performance and enhancing the feasibility of its use.

3. A.W. Warner and B. Goldfrank, "Lateral Field Resonators" 39th FCS p. 473, 1985.

4. U.S. Patent 4701661 "Piezo Electric Resonators Having a Lateral Field Excited SC Cut Quartz Crystal Elements."

Blank Fabrication and Processing.

All work on the first two contracts used a 0.55 inch (14mm) diameter crystal blank while the current study used a 0.59 inch (15mm) diameter crystal blank. The testing indicates that a larger crystal blank has improved performance, by reducing the "C" mode resistance. We were unable to study larger crystals under the scope of this contract. It is possible that additional improvements could be made by fabricating larger crystal blanks.

Table 3 is a summary of the various crystal frequencies investigated during the contract. Four separate lots were made. The first crystals evaluated were cut at $\phi = 36.58°$ and $\theta = 26.00°$. These were fabricated as 10.0/3/AK and were also tested on the fundamental and fifth overtones. A second group of crystals with the same angles of cut were fabricated as 2.124/F/AK, and tested on all overtones where meaningful responses were obtained. We defined meaningful response as a frequency response with a resistance less than 800 Ω. This group of crystals was subsequently reprocessed and retested at 2.500/F/AK and 5.00/F/AK. A third group of crystals was then fabricated at 3.0/F/AK. These crystals were then reprocessed into 4.0/F/AK crystals. A final group of AK ($\phi = 36.58°$, $\theta = 26.00°$) crystals was fabricated at 3.0/F/AK for the lateral field experiments (AK-LFR). These crystals are also shown in Table 3.

After the AK-LFR blanks were fabricated they were tested for electric field rotation, omega ω. ω is defined as field rotation from the -x axis of the quartz blank.[5,6] Testing consisted of rotating the field, ω, in 30° increments and evaluating the blank resistance response. Two field rotations, $\omega = 105°$ and $\omega = 225°$ were found to have reasonably low resistances. The AK-LFR crystals were processed using a variety of field rotations about these two angles.

An additional group of crystals was cut at $\phi = 35.00°$ and $\theta = 25.00°$. These were processed initially as 2.00/F/AK crystals, and then reprocessed as 10.0/3/AK crystals, which is equivalent to a 3.4/F/AK. The crystals with a 10.0 diopter curvature were tested at 2.8 MHz. The edge thickness would have been too thin, resulting in large edge chips, if we had attempted to increase the frequency to 3.4 MHz.

All the AK-cut crystals fabricated were cut from pure Z, Premium Q, unswept, cultured quartz bars. The AK crystals were pasted in "C" headers and were supported at three points, 90° apart (see Figure 1), except for the AK-LFR crystals which were supported at four points, 90° apart.

5. Final Report "Development of SC-Cut Lateral Field Resonators" LABCOM, Fort Monmouth, NJ, Contract DAAK20-83-C-0418-3.

6. U.S. Patent 4,701,661, Oct. 20, 1987

Results.

As the various lots were processed and tested, the following observations were made.

Table 4 shows that the "C" to "B" mode ratio was reasonably constant for all overtones with varying curvatures. The curvature is always listed in diopters. The actual radius of curvature in inches is defined as:

$$R_c = \frac{20.866}{\text{diopter number}}$$

The ratios $3F_F/F_3$ and $5F_F/F_5$ increased with increasing curvature. This is also shown in Table 5. These ratios also seem to vary slightly with frequency and angles of cut as shown in Table 5.

The turnover temperatures decrease with increasing curvature on the fundamental and fifth overtones. The third overtone turnover appears to remain constant, while the first anharmonic of the third overtone showed an increase in turnover with increasing curvature as shown in Table 6.

The thickness constant increases with increasing curvature. Table 7 shows the average thickness constants for the AK cuts fabricated, varying both the frequency and radius of curvature. Figure 2 shows the same data, in graph form. Note that the 2.0/2.1 MHz data lines are essentially parallel, as are the 3.0/3.4 MHz data lines.

The resistance increases with increasing curvature, as shown in Table 8, with a subsequent decrease in Q, on the fundamental "C" mode.

Lighter plate-backs, or the amount of metal deposited on the surface of the resonator, appear to degrade performance. Only $1.0F^2$ and $0.5F^2$ were used in the comparison. $1.0F^2$ (in kHz) is defined as the fundamental frequency (in MHz), squared, times the overtone, ($1.0F^2 = \left(\frac{f}{n}\right)^2 \times n$, where f is the crystal frequency and n is the overtone.) This term is also used as a design tool to insure that the proper blank frequency is obtained, by adding the designed plate-back to the desired final frequency. For example, a 3.0 MHz, fundamental mode AK cut thickness field resonator with a designed plate-back of $0.85F^2$ should have a polished blank frequency of 3.007650 MHz. There was a 40% increase in resistance, with a resultant reduction in Q, using the lower plate-back, as shown in Table 9. Plate-back variations may warrant further investigation.

A larger blank diameter and a larger electrode diameter reduces the resistance and improves the Q as shown in Table 10. Both sets of angles tested showed improvement in both R and Q over the previously fabricated crystals which were all 0.550 inch diameter, with a 0.265 inch diameter electrode. This suggests that the larger crystal size should be used.

Tables 11 and 12 show the typical "G" data obtained. The "G" sensitivity on the third overtone of the AK crystal is approximately three times better than on the fundamental. The "G" data is comparable on the fundamental and third overtone to similar SC cut crystals. Note also that increasing the electrode diameter improves the "G" sensitivity on the AK-cut crystal as shown in Table 13. This is similar to the previously reported improvement in resistance. No effort was made on this program to try to optimize the "G" performance.

The AK-LFR crystals were quite successful. Typical fundamental mode lateral field data is contained in Table 14. Included with this data is the angle of rotation $\vec{\omega}$ of the field. Most of the spurious modes, including the "B" mode and some higher overtones, were suppressed. Figures 3A through 3F are typical mode spectra for a 3.0 MHz perpendicular field fundamental mode AK cut crystal with a 4.13 diopter curvature. Figures 4A through 4G show a similar crystal, fabricated as an AK-LFR with a 0.075 inch gap at $\vec{\omega} = 105°$.

Note that on all spur plots, the depicted level does not represent the actual strength. The actual levels were determined by peaking in each response on an HP3577A network analyzer using the smallest span possible. The actual levels are recorded on each spur plot.

An Appendix is attached to this report. It contains additional data similar to that presented in the preceding text. Its purpose is to provide additional information as well as to show the uniformity with which AK cut resonators may be fabricated.

Conclusions.

The AK-cut crystal makes an excellent fundamental mode resonator, both in a perpendicular and lateral field excitation. The current useful range is approximately 2.8 MHz to 4.7 MHz for the two sets of angles studied, based on typical performance data, and the desire to maximize Q. For SC cut crystals, oscillators are designed to suppress the "B" mode. The same oscillators can be utilized to suppress the "B" mode for AK-cut crystals.

The blank geometry must be plano-convex with a minimum diameter of 0.55 inches. Epoxy mount techniques are required because of small edge thicknesses.

The lateral field design suppresses most of the spurious responses, particularly the "B" mode. Additional investigations of the AK fundamental mode are required to further understand the suppression of the anharmonics and spurious modes so that the circuit design can be simplified by removing the "B" mode trap, and thus reducing the cost.

The "G" sensitivity of the AK crystal on the third overtone is better than that of the AT cut, and comparable to similar SC cut units. Improvement would require a separate study program to determine optimum mounting.

Recommended AK Crystal Specifications.

1. Optimum fundamental frequency range between 2.8 MHz and 4.7 MHz.
2. Optimum curvature is between 2.5 and 6.0 diopters (8.346 inch radius of curvature to 3.478 inch radius of curvature, respectively).
3. Minimum electrode diameter is 0.265 inches.
4. Minimum crystal blank diameter is 0.550 inches.
5. Minimum designed plate-back is estimated at $.85F^2$. This is based on the presented data and our experience with SC cut crystals.

Proposed Future Studies.

1. AK cut crystals with higher ϕ angles that have higher "C" to "B" mode ratios. This recommendation is made because lower turnover temperatures can be achieved through contouring.

2. AK lateral field crystal study to evaluate curvature, electrode spacing, and field direction angle ($\vec{\omega}$).

3. Large diameter AK cut crystal evaluation. The purpose of this study would be to increase the useful frequency range by using a 0.986 inch diameter crystal, because lower frequencies could be evaluated and improvements in the mounting techniques, such as thermo-compression bonding, may become feasible, because the edge of the crystal blank will be thicker.

4. "G" sensitivity study on current designs. Determination of optimum mounting angle and techniques. This could be combined with proposal three above.

5. Evaluate an optimized design in a standard ceramic flat pack. Trade-offs would have to be made due to lower Q with a smaller blank diameter. The advantage of the ceramic flat pack include better mounting techniques, limited air exposure during processing and lower vacuum levels during sealing.

TABLE 1

FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS

		"C" MODE			"B" MODE		
Ø/θ	SER. NO.	F_S (Hz)	R	T.O. (°C)	F_S (Hz)	R	T.O. (°C)
46.06°/23.55°	9338	3361422	<10Ω	136°	3622437	>500	NA
	9339	3361117	<10Ω	136°	3622716	>500	NA
	9340	3361381	<10Ω	136°	3621094	>500	NA
	9342	3360750	<10Ω	136°	3617986	>500	NA
40.90°/23.55°	9980	3356768	<10Ω	95°	3726759	140Ω	NA
	9981	3357249	<10Ω	95°	3726951	50Ω	NA
	9982	3357024	<10Ω	95°	3726945	60Ω	NA
36.00°/24.44°	10132	3368171	10Ω	78°	3793594	20Ω	NA
	10134	3367539	28Ω	78°	3798211	80Ω	NA
40.90°/21.00°	10123	3356390	60Ω	115°	3912582	20Ω	NA
	10124	3357853	36Ω	115°	3914411	40Ω	NA
	10125	3357370	28Ω	115°	3913607	20Ω	NA
40.9°/27.00°	9991	3557338	<10Ω	104°	3540515	60Ω	NA
	9992	3365651	<10Ω	104°	3554006	40Ω	NA

Data presented was taken during initial AK study under P.O. Number F19650-82-B-0578

NA = Not applicable

TABLE 2

FREQUENCY, RESISTANCES AND TURNOVER TEMPERATURES OF FUNDAMENTAL "C" AND "B" MODE RESPONSES FOR AK CRYSTALS

		"C" MODE			"B" MODE		
Ø/θ	SER. NO.	F_S (Hz)	R	T.O. (°C)	F_S (Hz)	R	T.O. (°C)
33.00°/24.44°	14322	3380101	80Ω	95°	3865564	145Ω	NA
	14325	3381189	110Ω	95°	3864619	90Ω	NA
	14327	3380725	60Ω	95°	3857568	60Ω	NA
	14328	3380014	50Ω	95°	3858736	60Ω	NA
34.00°/22.00°	14332	3380450	55Ω	115°	4007522	50Ω	NA
	14338	3379060	105Ω	115°	4006092	80Ω	NA
	14339	3380311	145Ω	115°	4006070	55Ω	NA
	14340	3379987	170Ω	115°	4996473	80Ω	NA
	14341	3379919	200Ω	115°	4006437	40Ω	NA
34.00°/26.00°	14349	3381447	60Ω	81°	3748189	110Ω	NA
	14350	3382619	205Ω	81°	3750043	275Ω	NA
	14351	3382448	145Ω	81°	3749148	300Ω	NA
34.00°/28.44°	14358	3380665	500Ω	106°	3622914	90Ω	NA
	14360	3380312	500Ω	106°	3623723	80Ω	NA
	14365	3381266	>500Ω	106°	3629341	145Ω	NA
36.58°/22.00°	14373	3384436	30Ω	90°	3948761	15Ω	NA
	14375	3384011	15Ω	90°	3948741	15Ω	NA
	14376	3383489	20Ω	90°	3948896	20Ω	NA
36.58°/26.00°	14386	3394076	40Ω	76°	3713306	450Ω	NA
38.50°/26.00°	14398	3404212	30Ω	81°	3690441	110Ω	NA
	14399	3404481	10Ω	81°	3688878	80Ω	NA

Data presented was taken during second AK study under P.O. Number F19650-83-M-0713

NA = Not applicable

TABLE 3

SUMMARY OF TYPES OF AK CUT RESONATORS FABRICATED
(All are perpendicular field resonators, except where noted.)

ANGLES OF CUT: $\emptyset = 36.58°$, $\theta = 26.00°$				ANGLES OF CUT: $\emptyset = 35.00°$, $\theta = 25.00°$			
NOMINAL FREQUENCY (IN MHz) BY OVERTONE			CURVATURE (IN DIOPTERS)	NOMINAL FREQUENCY (IN MHz) BY OVERTONE			CURVATURE (IN DIOPTERS)
F	3	5		F	3	5	
2.124	6.27	10.51	1.75, 2.63, 4.13, 10.0, 13.0	2.000	5.80	9.90	1.75, 2.63, 4.13, 10.0
2.500	7.38	12.38	4.13, 6.0, 8.0, 10.0				
3.000	8.8	14.85	4.13, 6.0, 8.0, 10.0	2.8			10.0
3.331	10.0	16.78	1.75, 2.63, 4.13				
4.000	11.9	19.80	4.13	3.45	10.0	16.78	4.13, 6.0, 8.0,
5.000	14.8	N.D.	1.75, 2.63, 4.13				
3.000	8.8	13.80	4.13*				

*Lateral Field AK cut resonators.

NOTES:

1. CRYSTAL FREQUENCY 3.391000 MHz
2. ITEM 2 WELDED TO ITEM 4
3. ITEM 1 ATTACHED TO ITEM 2 WITH ITEM 5
4. ITEM 3 COLD WELDED TO ITEM 4
5. ITEM 3 MARKED WITH ITEM 6

REVISIONS: RELEASED

QUANTITY	FEI PART NO	DESCRIPTION	ITEM NO
	7224	INK, BLACK	6
	5504	EPOXY	5
1	C 16203-883	HEADER 'C'	4
1	27741-883-2	COVER C	3
3	B 27572-883-1	MOUNT	2
1		QUARTZ CRYSTAL	1

MATERIALS AND TABULATED ITEMS

FINAL

FOR DRAFTING USE ONLY: B 20773-883

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES AND INCLUDE CHEMICALLY APPLIED FINISHED

TOLERANCES: ±.010 ±3°

B. AEBLI

FREQUENCY ELECTRONICS, INC.
NEW HYDE PARK, NEW YORK, 11040

AK RESONATOR ASSEMBLY

CODE IDENT NO 14844 | SIZE B | DRAWING NO 39250-9586 | REV A

DO NOT SCALE DRAWING | SHEET 1 OF 2

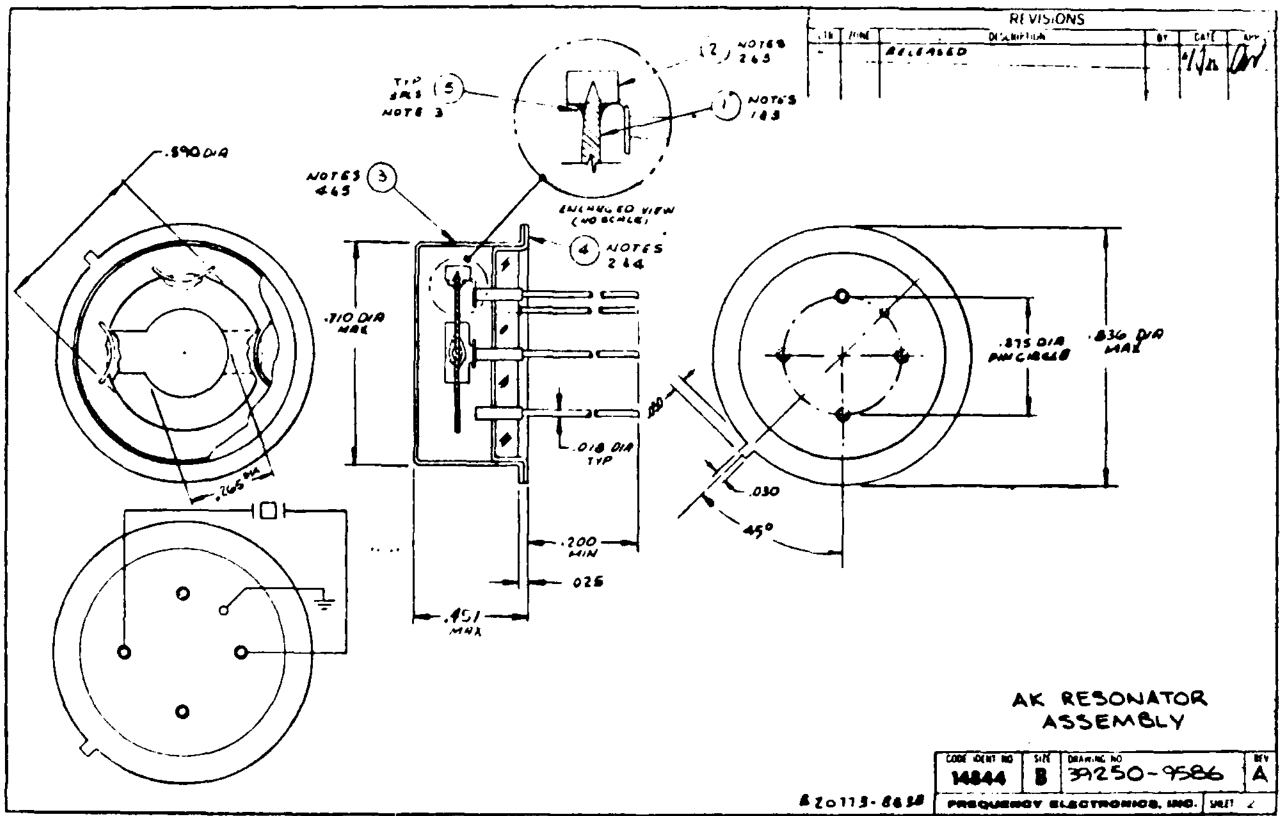


FIGURE 1

TABLE 4

MODE AND OVERTONE RATIOS FOR SELECTED AK-CUT CRYSTALS

NOMINAL FUNDAMENTAL FREQUENCY	ANGLES OF CUT	CURVATURE [4]	C/B RATIOS			C MODE RATIOS	
			F	3d	5th	$3F_F/F_3$	$5F_F/F_5$
2.00 MHz	ϕ = 35.00°	1.75	.8908	.8908	.8649	1.019	1.048
	θ = 25.00°	2.63	.8907	N.D.[1]	N.D.[1]	1.022	N.D.[1]
		4.13	.8899	.9301	.8640	1.027	1.058
		10.0	.9102	.8795	.8638	1.040	1.074
2.124 MHz	ϕ = 36.58°	1.75	.9104	.9027	.9107	1.019	1.018
	θ = 26.00°	2.63	.9105	.9024	.9102	1.022	1.020
		4.13	.9112	.9020	.9102	1.029	1.028
		10.0	.9131[2]	.9006[3]	.9102	1.041	1.041
		13.5	.9156	.8973	.9116	1.049	1.048
3.000 MHz	ϕ = 36.58°	6.0	.9244	.9050	.9165	1.0289	1.0264
	θ = 26.00°	8.0	.9182	.9022	.9166	1.0327	1.0302
		10.0	.9112	.9015	.9086	1.0356	1.0371
3.391 MHz	ϕ = 36.58°	1.75	.9116	.9047	.9113	1.0161	1.0139
	θ = 26.00°	2.63	.9112	.9037	.9113	1.0190	1.0168
		4.13	.9116	.9018	.9111	1.0229	1.0210
4.000 MHz	ϕ = 36.58° θ = 26.00°	4.13	.9142	.9053	.9148	1.0217	1.0192

1. No data, responses unstable.
2. Averaged data due to split mode.
3. Estimated.
4. Curvature in diopters.

TABLE 5

TYPICAL VALUES OF $3F_F/F_3$ FOR VARIOUS AK-CUT CRYSTALS
(DATA SELECTED FROM TABLE 4)

	$\phi = 36.58°$, $\theta = 26.00°$		$\phi = 35.00°$, $\theta = 25.00°$
CURVATURE[1]	$3F_F/F_3$ (10.0 MHz/3)	$3F_F/F_3$ (2.124 MHz/F)	$3F_F/F_3$ (2.0 MHz/F)
1-3/4 D	1.016	1.020	1.019
2-5/8 D	1.019	1.022	1.022
4-1/8 D	1.023	1.029	1.027
10 D	N/D[2]	1.041	1.040
13-1/2 D	N/D[2]	1.047	N/D[2]

1. Curvature in diopters.
2. No data.

TABLE 6

AVERAGE TURNOVER TEMPERATURE VS. CURVATURE AND ANGLES OF CUT

ANGLES OF CUT	NOMINAL FREQUENCY FUNDAMENTAL	RADIUS OF CURVATURE IN DIOPTERS	TURNOVER TEMPERATURE BY OVERTONE			
			1st	3d	5th	3d[1]
∅ = 36.58° θ = 26.00°	2.1 MHz	4.13 10.00	67 55	N.D.[2] N.D.[2]	N.D.[2] N.D.[2]	N.D.[2] N.D.[2]
∅ = 36.58° θ = 26.00°	3.4 MHz	1.75 2.63 4.13	81 75 74	69 68 70	74 75 72	93 96 N.D.[2]
∅ = 36.58° θ = 26.00°	5.0 MHz	1.75 2.63 4.13	80 77 76	N.D.[2]	N.D.[2]	N.D.[2]
∅ = 35.00° θ = 25.00°	2.1 MHz	4.13 10.00	70 60	93 99	N.D.[2] N.D.[2]	N.D.[2] N.D.[2]
∅ = 35.00° θ = 25.00°	2.8 MHz	10.00	63	N.D.[2]	N.D.[2]	N.D.[2]
∅ = 35.00° θ = 25.00°	3.4 MHz	4.13 5.00 8.00	75 72 68	N.D.[2]	N.D.[2]	N.D.[2]

1. Second third overtone. First third overtone 10.010 MHz with a 450 ohm resistance; second third overtone 10.060 MHz with a resistance of 250 ohms.

2. N.D. = no data. Resistance of overtone greater than 800Ω or so unstable as to prohibit equipment from tracking frequency versus temperature.

TABLE 7

AVERAGE FREQUENCIES, THICKNESSES AND THICKNESS CONSTANTS FOR AK-CUT CRYSTALS

ANGLES OF CUT	CURVE DIOPTERS	NOMINAL FREQUENCY (FUNDAMENTAL) IN MHz	THICKNESS INCHES (mm)	THICKNESS CONSTANT X 10^{4} (kHz-in)
Ø = 36.58° θ = 26.00°	1.75	2.127482	.037157 (.9438)	79.05
	2.625	2.127942	.037244 (.9460)	79.25
	4.125	2.127818	.037555 (.9539)	79.91
	10.0	2.127935	.038212 (.9706)	81.31
	4.125	3.008863	.026472 (.6724)	79.65
	6.0	3.009053	.026638 (.6788)	80.16
	8.0	3.009309	.026772 (.6800)	80.56
	10.0	3.009783	.026787 (.6804)	80.66
Ø = 35.00° θ = 25.00°	1.75	2.003645	.038720 (.9835)	77.58
	2.625	2.004097	.038890 (.9878)	77.94
	4.125	2.003921	.039173 (.9950)	78.50
	10.0	2.003869	.039882 (1.0130)	79.92
	4.125	3.423285	.022646 (.5752)	77.80
	6.0	3.450943	.022677 (.5760)	78.26
	8.0	3.463886	.022716 (.5770)	78.68
	10.0	2.780897	.028543 (.7250)	79.38

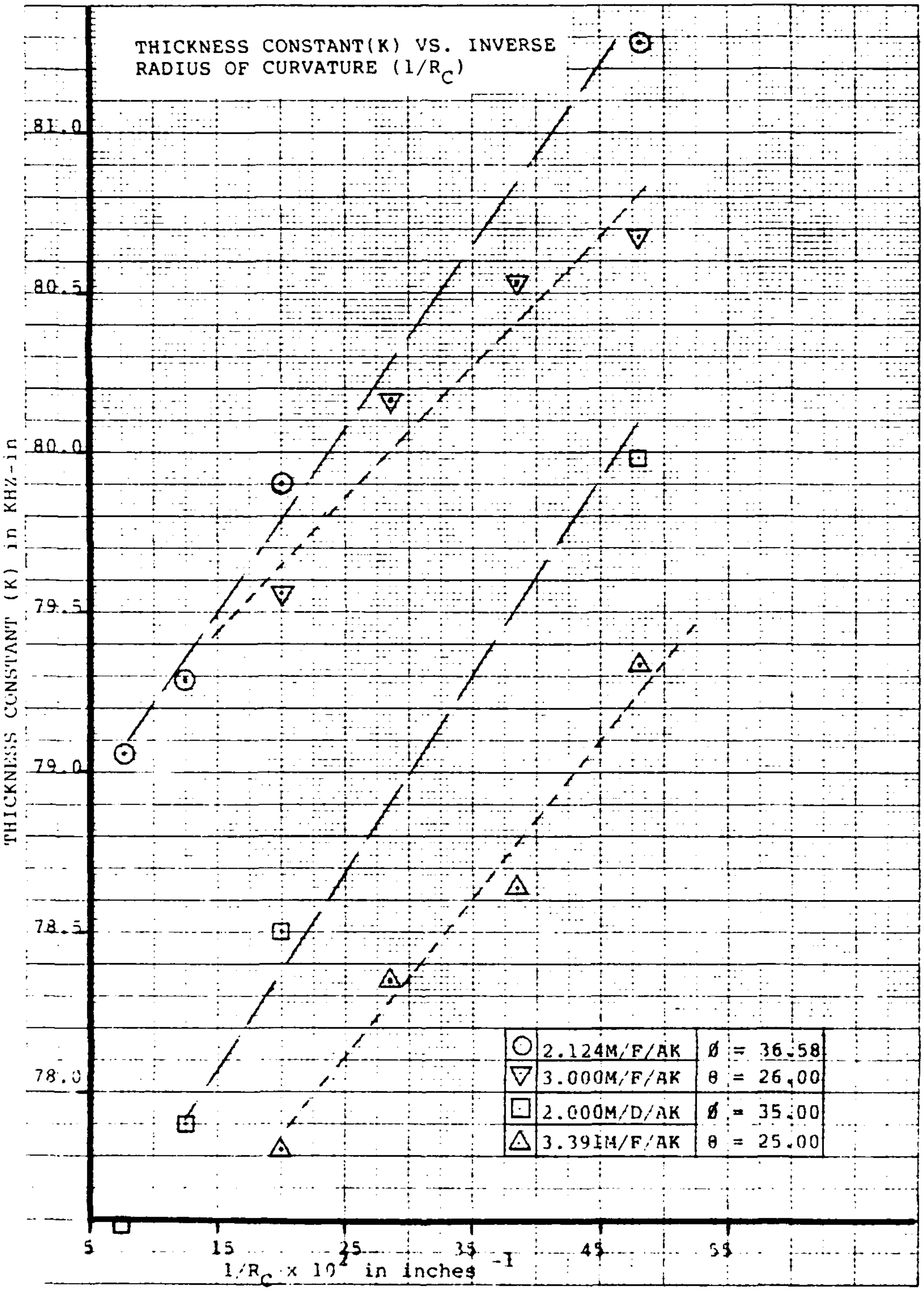

THICKNESS CONSTANT(K) VS. INVERSE
RADIUS OF CURVATURE ($1/R_C$)
THICKNESS CONSTANT (K) in KHZ-in
81.0
80.5
80.0
79.5
79.0
78.5
78.0
5
15
25
35
45
55
$1/R_C \times 10^2$ in inches^{-1}
2.124M/F/AK ø = 36.58
3.000M/F/AK θ = 26.00
2.000M/D/AK ø = 35.00
3.391M/F/AK θ = 25.00

FIGURE 2

TABLE 8

TYPICAL AK-CUT DATA AT 3.0 MHz (FUNDAMENTAL "C" MODE)
($\emptyset$ = 36.58°, θ = 26.00°)

Designed Plate Back = $1.0F^2$

CURVATURE	f_s @ 25°C	R (Ω)	f_p @ 25°C w/C_L	Δf	C_o	C_1 X 10^{+16}	Q X 10^{-6}
4.13	3003197	25	3003317	120	3.2	10.5	2.0
	3002833	22	3002957	124	3.2	10.9	2.2
6.0	3003258	27	3003364	106	3.2	9.3	2.1
	3003176	33	3003278	102	3.2	9.0	1.8
8.0	3003268	44	3003267	99	3.2	8.8	1.4
	3002975	38	3003072	97	3.2	8.6	1.6
10.0	3003463	175	3003548	85	3.2	7.5	0.4
	3003288	225	3003374	86	3.2	7.6	0.3

$$\Delta f = f_p - f_s$$

$$C_1 = \frac{2\,(\Delta f) \times (C_o + C_L)}{f_s} \quad \text{where } C_L = 10 \text{ pf}$$

$$Q = \frac{1}{2\pi f_s R C_1}$$

TABLE 9

ROOM TEMPERATURE DATA FOR $1.0F^2$ and $0.5F^2$ PLATE BACK

PLATE BACK	SER. NO.	f_s @ 25°C	R	f_p @ 10 pf @ 25°C	Δf $(f_p - f_s)$	C_o	C_1 x 10^{+16}	Q x 10^{-6}
$1.0F^2$	23124	4004005	19	4004161	156	3.8	1.1	1.9
	23125	4003480	18	4003639	159	3.8	1.1	2.0
	23126	4003706	18	4003865	159	3.8	1.1	2.0
	23127	4007475	22	4007613	138	3.8	1.0	1.9
$0.5F^2$	23124R	4010032	24	4010182	150	3.8	1.1	1.6
	23126R	4009236	22	4009390	154	3.8	1.1	1.7
	23127R	4012911	27	4013056	145	3.8	1.0	1.4

$$\Delta f = f_p - f_s$$

$$C_1 = \frac{2\,(\Delta f) \times (C_o + C_L)}{f_s} \quad \text{where } C_L = 10 \text{ pf}$$

$$Q = \frac{1}{2\pi f_s R C_1}$$

TABLE 10

COMPARISON OF R, C_1 AND Q AT TWO ELECTRODE DIAMETERS (.265" AND .221") FOR .550 AND .590 INCH DIAMETER AK-CUT CRYSTALS

		RESISTANCE R (OHMS)		$C_1 \times 10^{+16}$		$Q \times 10^{-6}$	
BLANK DIAM	CURVE	(.265")	(.221")	(.265")	(.221")	(.265")	(.221")
.590	4.13 D	16.01	22.32	.997	.842	2.93	2.51
.590	6.00 D	17.58	22.85	.878	.732	3.02	2.77
.590	8.00 D	27.4	41.34	.799	.692	2.12	1.62
.590	10.00 D	210.11	265.09	.736	.656	0.37	0.33
.550	4.13	40	ND	1.4	ND	0.88	ND

NOTE: Values shown are averages.

ND = No data.

TABLE 11

"G" SENSITIVITY DATA TAKEN ON THE FUNDAMENTAL AND THIRD OVERTONES OF VARIOUS AK-CUT CRYSTALS

ANGLES OF CUT: ϕ = 36.58°, θ = 26.00°									
3.4 MHz/F/AK				5.0 MHz/F/AK			3.0 MHz/F/AK		
SER. NO.	CURV.	Γ_{FUND} $(x10^{-10})$	Γ_{3D} $x10^{-10}$	SER. NO.	CURV.	FUND $(x10^{-10})$	SER. NO.	CURV.	Γ_{FUND} $(x10^{-10})$
001 002	1.75 1.75	24.5 18.7	7.72 3.91	21378	1.75	10.40			
001 002	2.625 2.625	31.6 21.4	6.62 4.55	21373	2.625	9.09			
004 005	4.125 4.125	22.3 17.6	5.55 5.99				23124	4.125	11.38
							23128	6.0	17.91
							23132	8.0	7.62
							20440RR	10.0	6.79

NOTE: F_{VIB} = 100 Hz, Electrode DIA = .265"

TABLE 12

"G" SENSITIVITY DATA TAKEN ON THE
THIRD OVERTONE OF VARIOUS AK-CUT CRYSTALS

ANGLES OF CUT: $\emptyset = 35.00°$, $\theta = 25.00°$					
10.0 MHz/3/AK			8.0 MHz/3/AK[1]		
SER. NO.	CURV.	Γ_{3D} ($\times 10^{-10}$)	SER. NO.	CURV.	Γ_{3D} ($\times 10^{-10}$)
20456R	4.125	5.92			
20448R	6.0	5.68			
20452R	8.0	5.68			
			20460R	10.0	7.05

NOTE: F_{VIB} = 100 Hz, Electrode DIA = .265"

[1]Approximately 2.8 MHz, fundamental.

TABLE 13

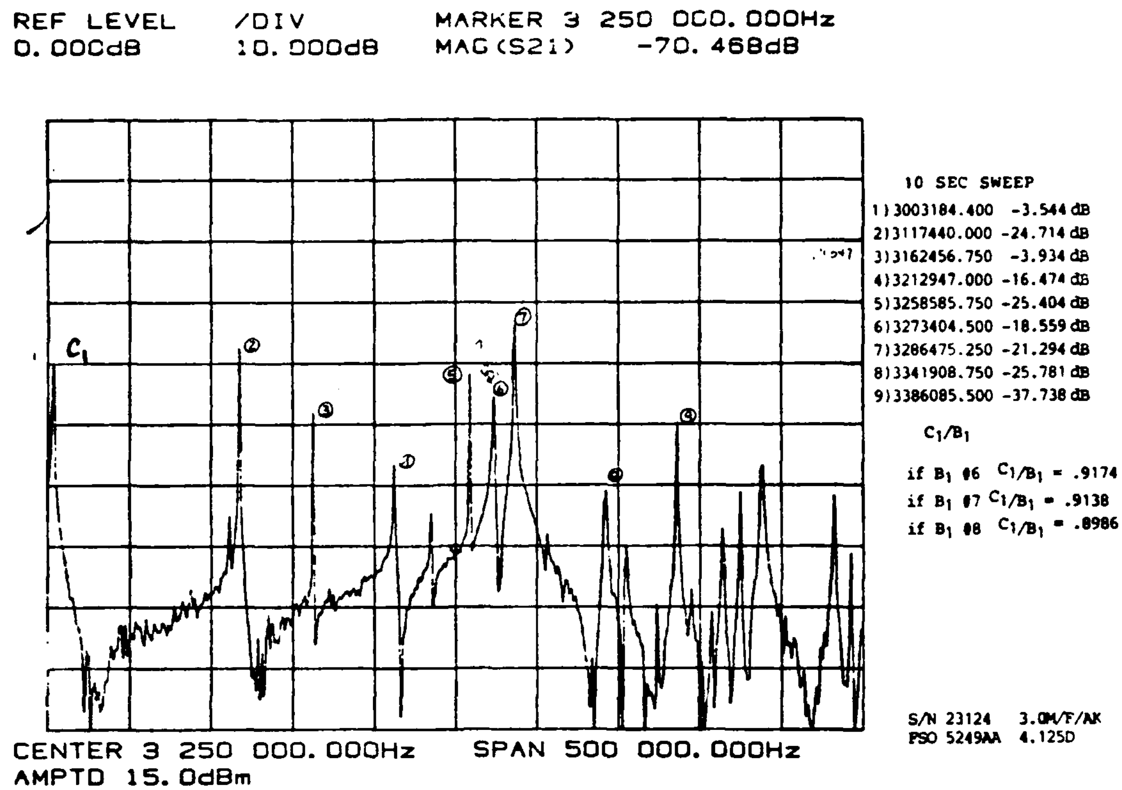
"G" SENSITIVITY OF THE 10.0 MHz/3/AK AND 8.0 MHz/3/AK CRYSTALS
WITH DIFFERENT ELECTRODE DIAMETERS
IN PARTS 10^{10}

ANGLES OF CUT: $\emptyset = 35.00°$, $\theta = 25.00°$		
CURVE	.265" ELECTRODE	.221" ELECTRODE
4.125	5.92	12.62
6.0	5.68	8.22
8.0	5.68	8.22
10.0	7.05	10.97

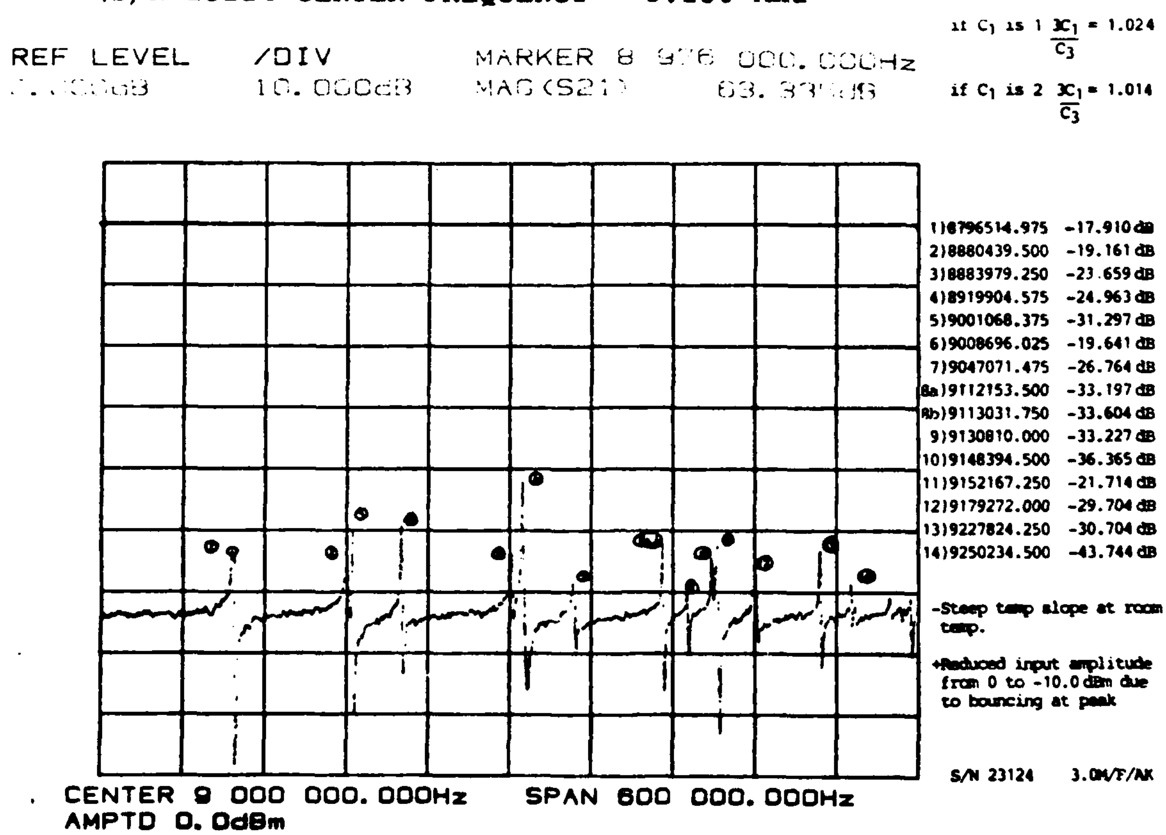
TABLE 14

AK LATERAL FIELD ROOM TEMPERATURE DATA FOR DIFFERENT FIELD ROTATION ANGLES ($\vec{\omega}$)

NO.	f_s @ 25°C	R (Ω)	f_p @ 25°C w/10 pf	Δf ($f_p - f_s$)	C_0	C_1 X 10^{+17}	Q X 10^{-6}	$\vec{\omega}$
2	3000914.5	570	3000920.3	5.8	0.61	4.09	2.27	60°
4	3001136.3	380	3001148.0	11.7	0.62	8.27	1.67	90°
6	3001310.6	480	3001318.6	8.0	0.61	5.65	1.96	105°
8	3001130.8	355	3001139.3	8.5	0.61	6.01	2.49	120°
12	3001381.9	645	3001387.1	5.2	0.60	3.67	2.24	255°



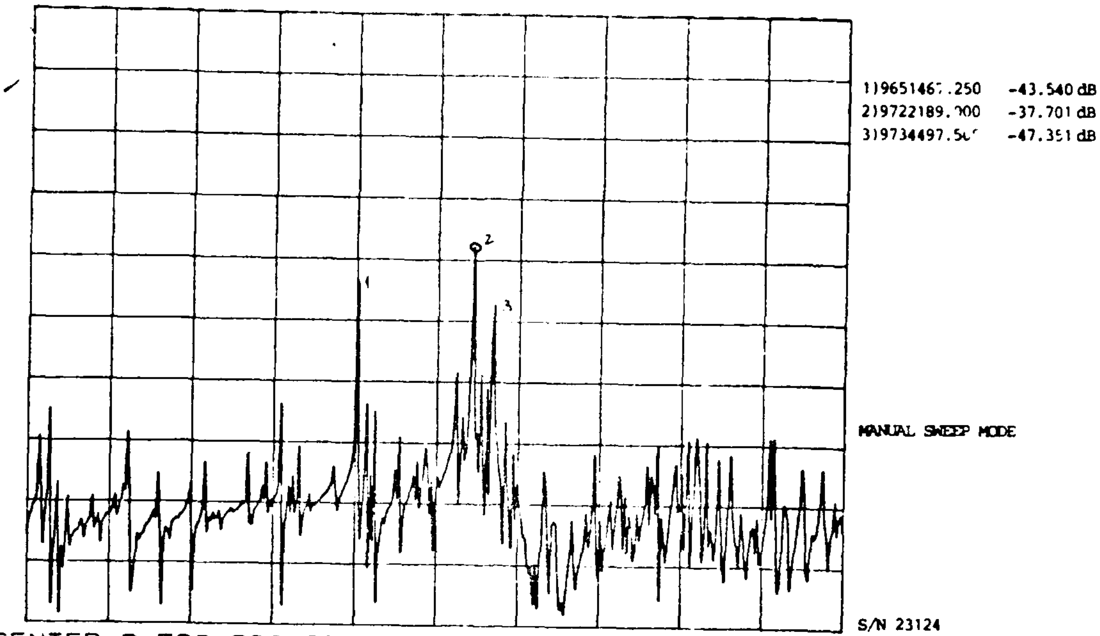
FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL OVERTONE,
'C' AND 'B' MODE ON AN AK-CUT CRYSTAL
:S/N 23124 CENTER FREQUENCY = 3.250 MHz



FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE,
'C' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 9.0 MHz

Figures 3a and 3b

REF LEVEL /DIV MANUAL 9 722 218.750Hz
0.000dB 10.000dB MAG(S21) -37.848dB



CENTER 9 700 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE,
'B' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 9.7 MHz

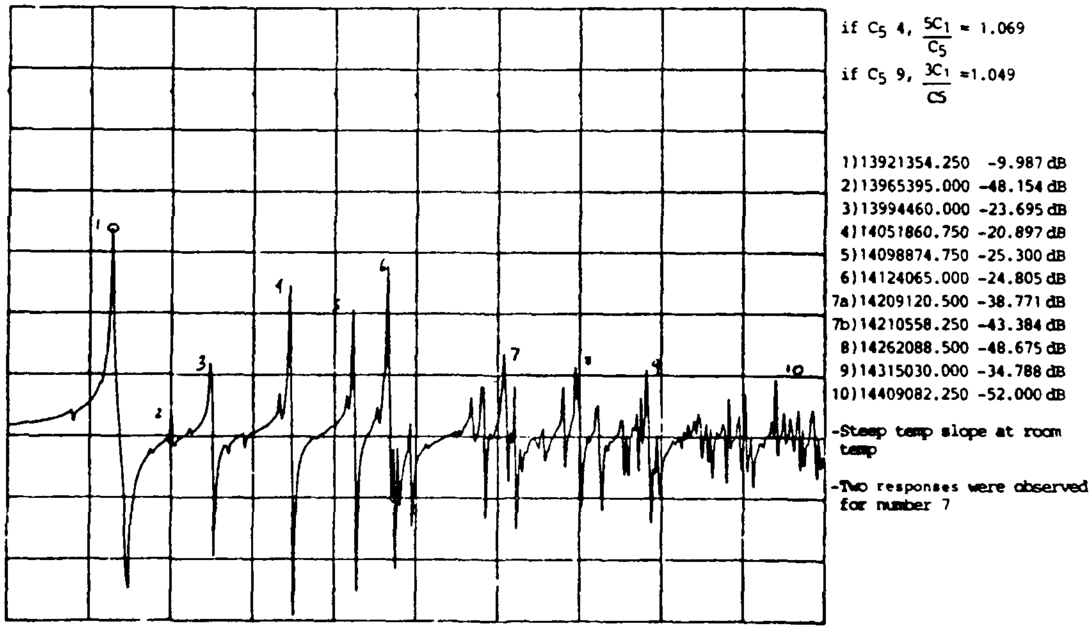
REF LEVEL /DIV MARKER 13 922 000.000Hz
0.000dB 10.000dB MAG(S21) -36.023dB

if C_5 1, $\frac{5C_1}{C_5} = 1.079$

if C_5 3, $\frac{5C_1}{C_5} = 1.072$

if C_5 4, $\frac{5C_1}{C_5} = 1.069$

if C_5 9, $\frac{3C_1}{C_5} = 1.049$



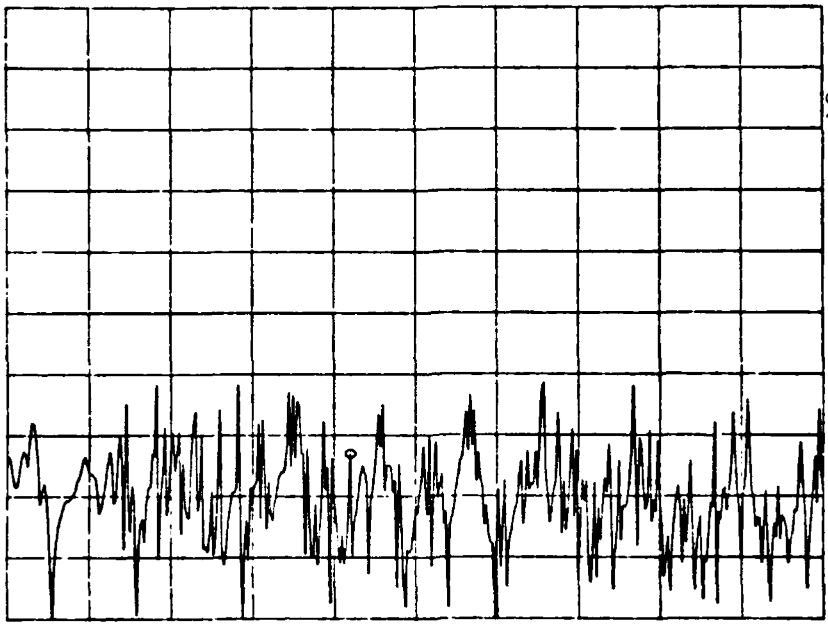
CENTER 14 145 500.000Hz SPAN 600 000.000Hz
AMPTD 0.0dBm

S/N 23124 3.0M/F/AK

FREQUENCY RESPONSE PLOT FOR UNIDENTIFIED
MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 14.1455 MHz

Figures 3c and 3d

REF LEVEL /DIV MARKER 14 552 000.000Hz
0.000dB 10.000dB MAG(S21) -72.991dB

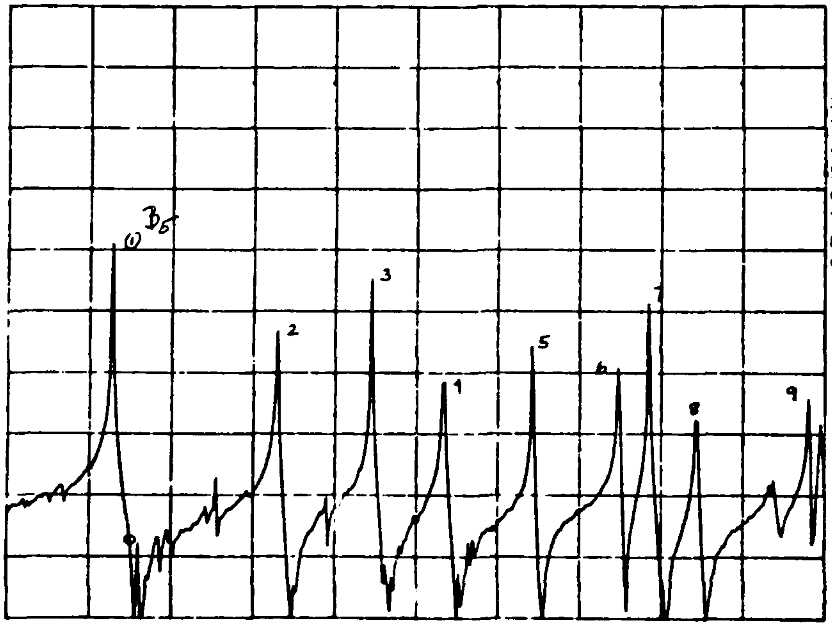


C_5 predicted to be
~ 14/6 MHz

CENTER 14 600 000.000Hz SPAN 600 000.000Hz S/N 23124
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE
'C' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 14.60 MHz

REF LEVEL /DIV MARKER 16 069 000.000Hz
0.000dB 10.000dB MAG(S21) -87.294dB



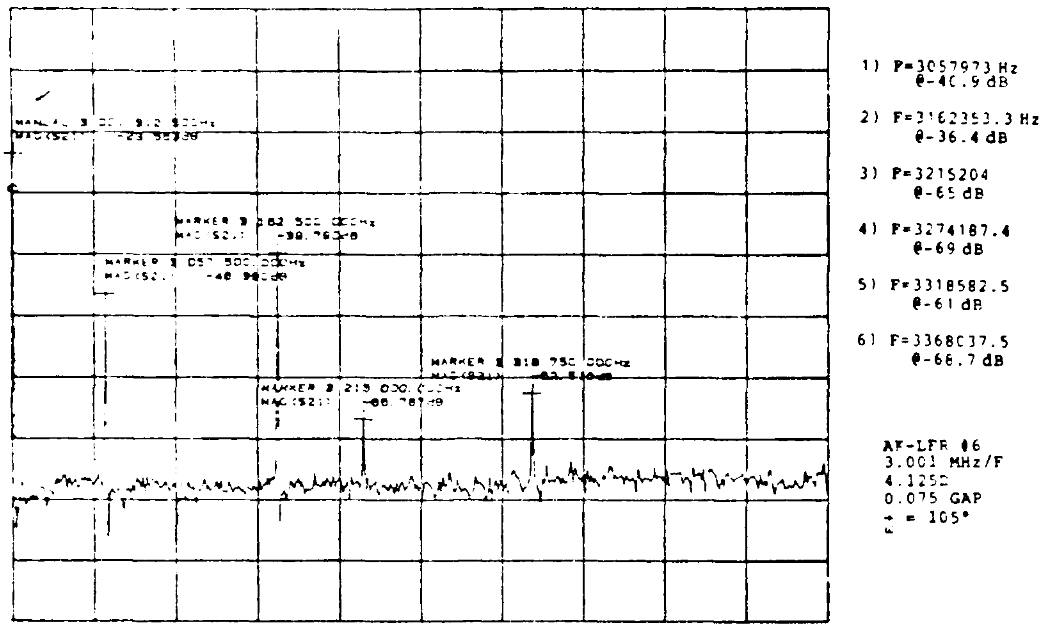
1)	16055124.300	-17.273 dB
2)	16176185.000	-39.973 dB
3)	16245706.500	-23.387 dB
4)	16298856.000	-38.020 dB
5)	16364404.700	-27.700 dB
6)	16427599.200	-43.230 dB
7)	16449808.500	-24.200 dB
8)	16484852.000	-50.227 dB
9)	16567204.000	-36.600 dB

CENTER 16 279 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm S/N 23124 3.0M/P/AK

FREQUENCY RESPONSE PLOT FOR 5TH OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N 23124 CENTER FREQUENCY = 16.279 MHz

Figures 3e and 3f

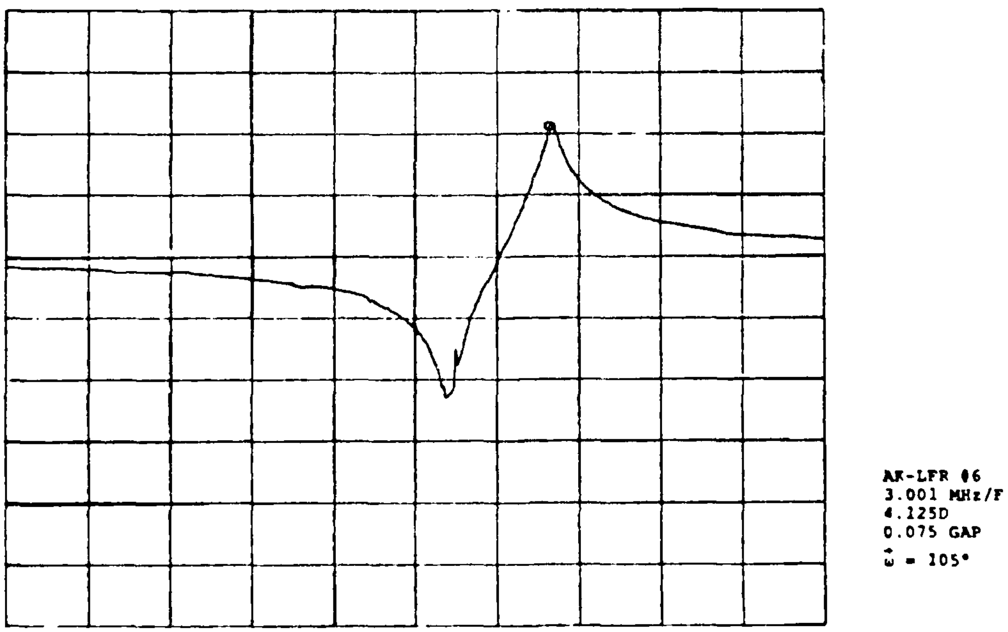
REF LEVEL /DIV MANUAL 3 001 312.500Hz 8-20-86
0.000dB 10.000dB MAG(S21) -29.458dB AK LFR #6



CENTER 3 250 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL
'C' MODE AND 'B' MODES ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 3.25 MHz

REF LEVEL /DIV MANUAL 3 001 316.618Hz AK LFR #6
0.000dB 10.000dB MAG(S21) -18.787dB 9-18

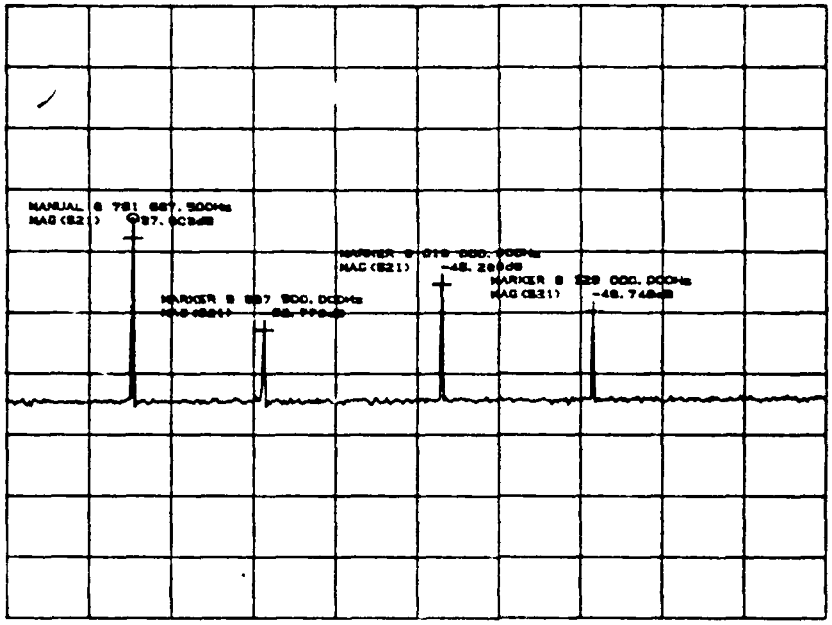


CENTER 3 001 300.000Hz SPAN 100.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FUNDAMENTAL
'C' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 3.0013 MHz

Figures 4a and 4b

REF LEVEL /DIV MANUAL 8 791 687.500Hz 9-18
0.000dB 10.000dB MAG(S21) -34.515dB AK LFR #6

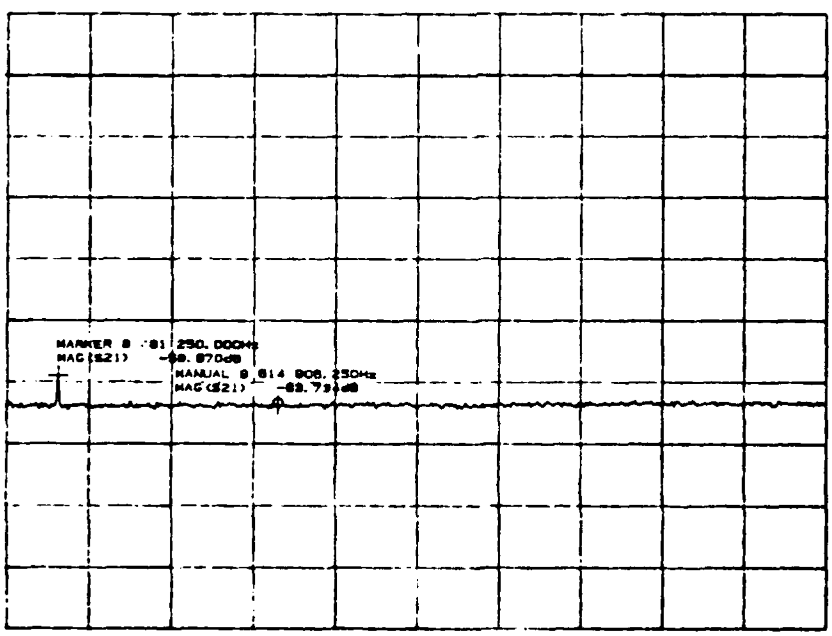


AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
$\vec{\omega}$ = 105°

CENTER 9 000 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE
'C' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 9.0 MHz

REF LEVEL /DIV MANUAL 9 614 906.250Hz 9-18
0.000dB 10.000dB MAG(S21) -63.373dB AK LFR #6



AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
$\vec{\omega}$ = 105°

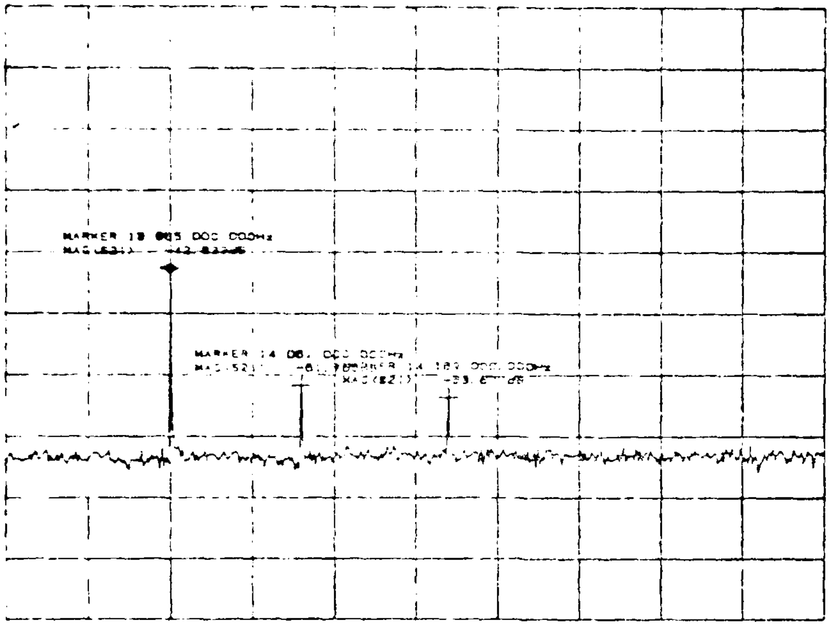
CENTER 9 700 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR THIRD OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 9.7 MHz

Figures 4c and 4d

REF LEVEL /DIV MARKER 13 965 000.000Hz
0.000dB 10.000dB MAG(S21) -42.633dB

9-18
AK LFR #6



AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
$\vec{\omega}$ = 105°

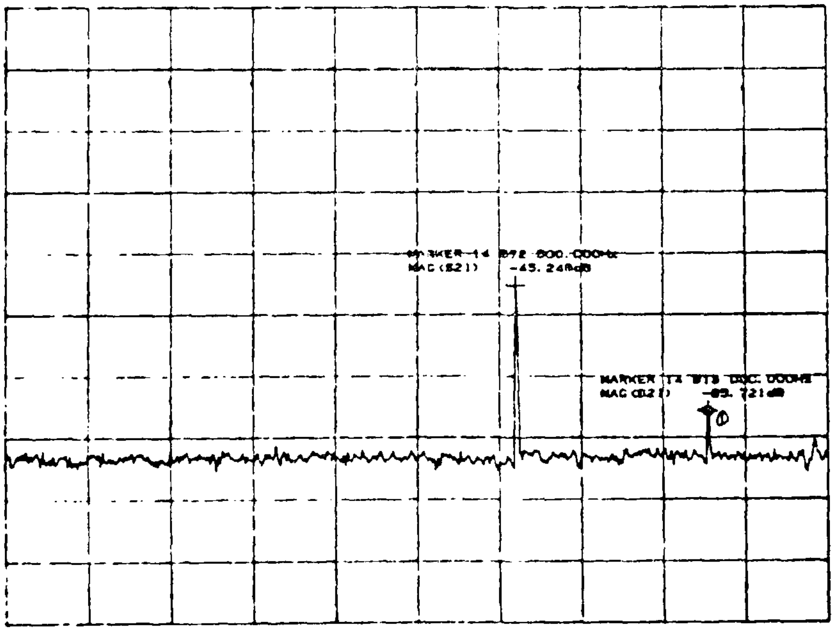
CENTER 14 145 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT UNIDENTIFIED MODE
ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 14.145 MHz

REF LEVEL /DIV MARKER 14 813 000.000Hz
0.000dB 10.000dB MAG(S21) -65.721dB

9-18
AK LFR #6

1) F=14813070 Hz
@-62 dB

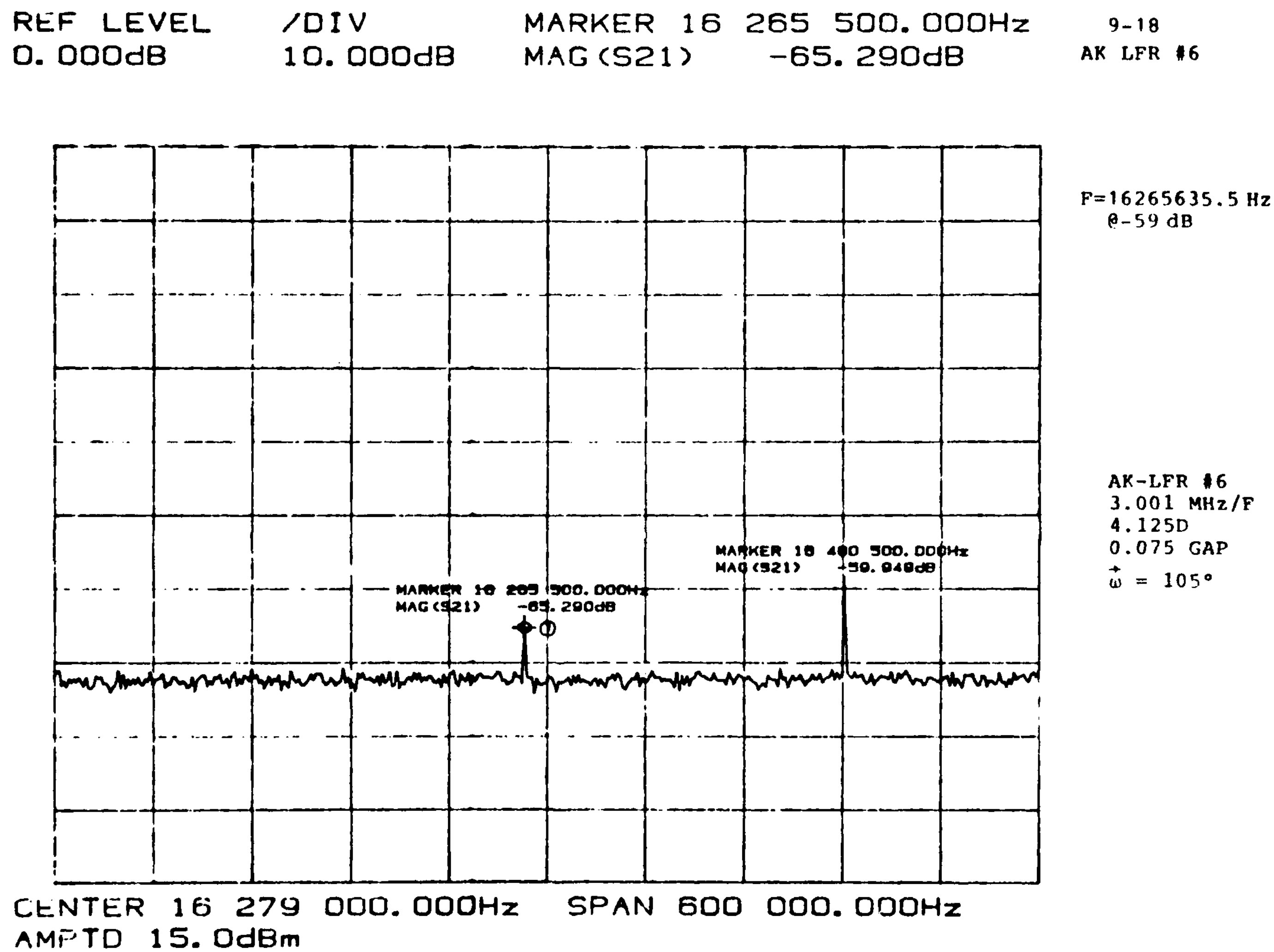


AK-LFR #6
3.001 MHz/F
4.125D
0.075 GAP
$\vec{\omega}$ = 105°

CENTER 14 600 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm

FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 14.60 MHz

Figures 4e and 4f



FREQUENCY RESPONSE PLOT FOR FIFTH OVERTONE
'B' MODE ON AN AK-CUT CRYSTAL
S/N AKLFR-6 CENTER FREQUENCY = 16.279 MHz

Figure 4g

APPENDIX

The accompanying appendix contains additional data on selected AK-cut crystals.

FIGURE(S)	DESCRIPTION
A-1	Quality Factor (Q) versus Fundamental Frequency for Various Curvatures and Platebacks
A-2 to A-5	Fundamental "C" Mode Temperature Slews
A-6 to A-10	Frequency Sweep Tables of Selected AK-Cut Crystals Listing Fundamental Third and Fifth Overtone Responses
A-11 to A-20	Frequency Response Plots for AK Resonators
A-21 to A-25	Frequency Response Plots for AK-LFR S/N 12

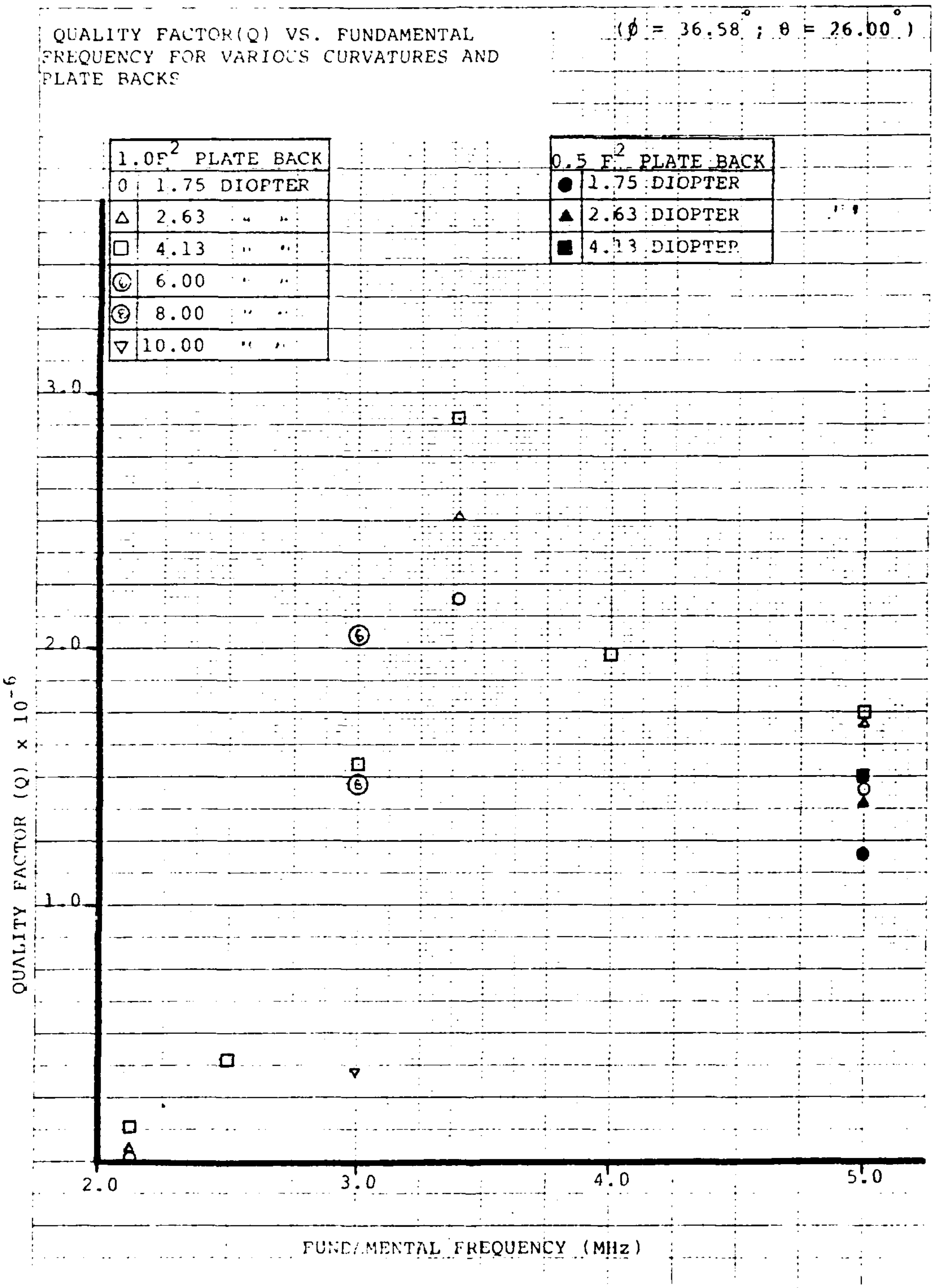

QUALITY FACTOR(Q) VS. FUNDAMENTAL FREQUENCY FOR VARIOUS CURVATURES AND PLATE BACKS
(ϕ = 36.58° ; θ = 26.00°)
1.0F² PLATE BACK
0 1.75 DIOPTER
△ 2.63 " "
□ 4.13 " "
6.00 " "
8.00 " "
▽ 10.00 " "
0.5 F² PLATE BACK
● 1.75 DIOPTER
▲ 2.63 DIOPTER
■ 4.13 DIOPTER
3.0
2.0
1.0
QUALITY FACTOR (Q) x 10⁻⁶
2.0
3.0
4.0
5.0
FUNDAMENTAL FREQUENCY (MHz)

FIGURE A-1

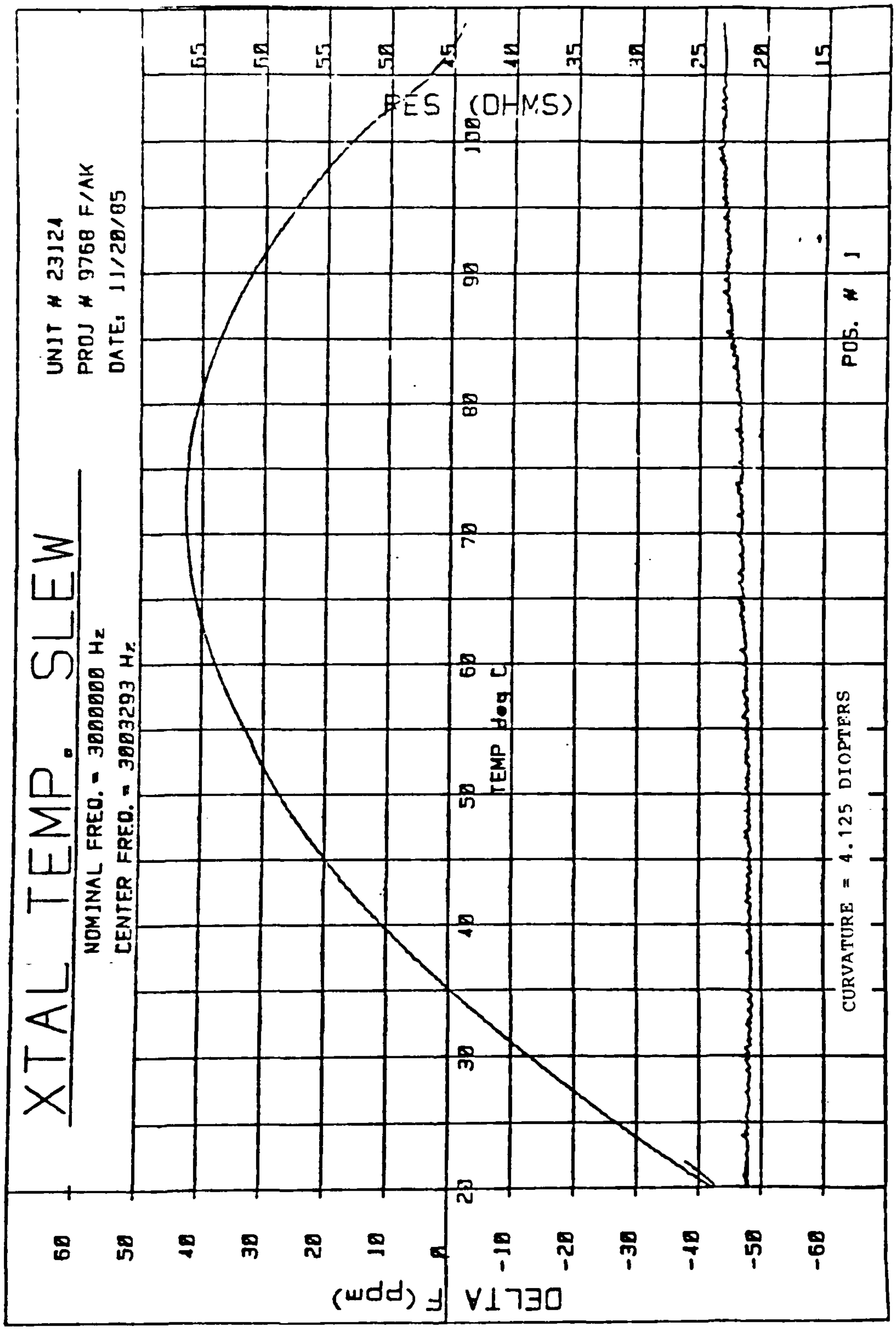

XTAL TEMP. SLEW
NOMINAL FREQ. = 3000000 Hz
CENTER FREQ. = 3003293 Hz
UNIT # 23124
PROJ # 9768 F/AK
DATE: 11/20/85
RES (OHMS)
TEMP deg C
DELTA F (ppm)
POS. # 1
CURVATURE = 4.125 DIOPTERS

FIGURE A-2

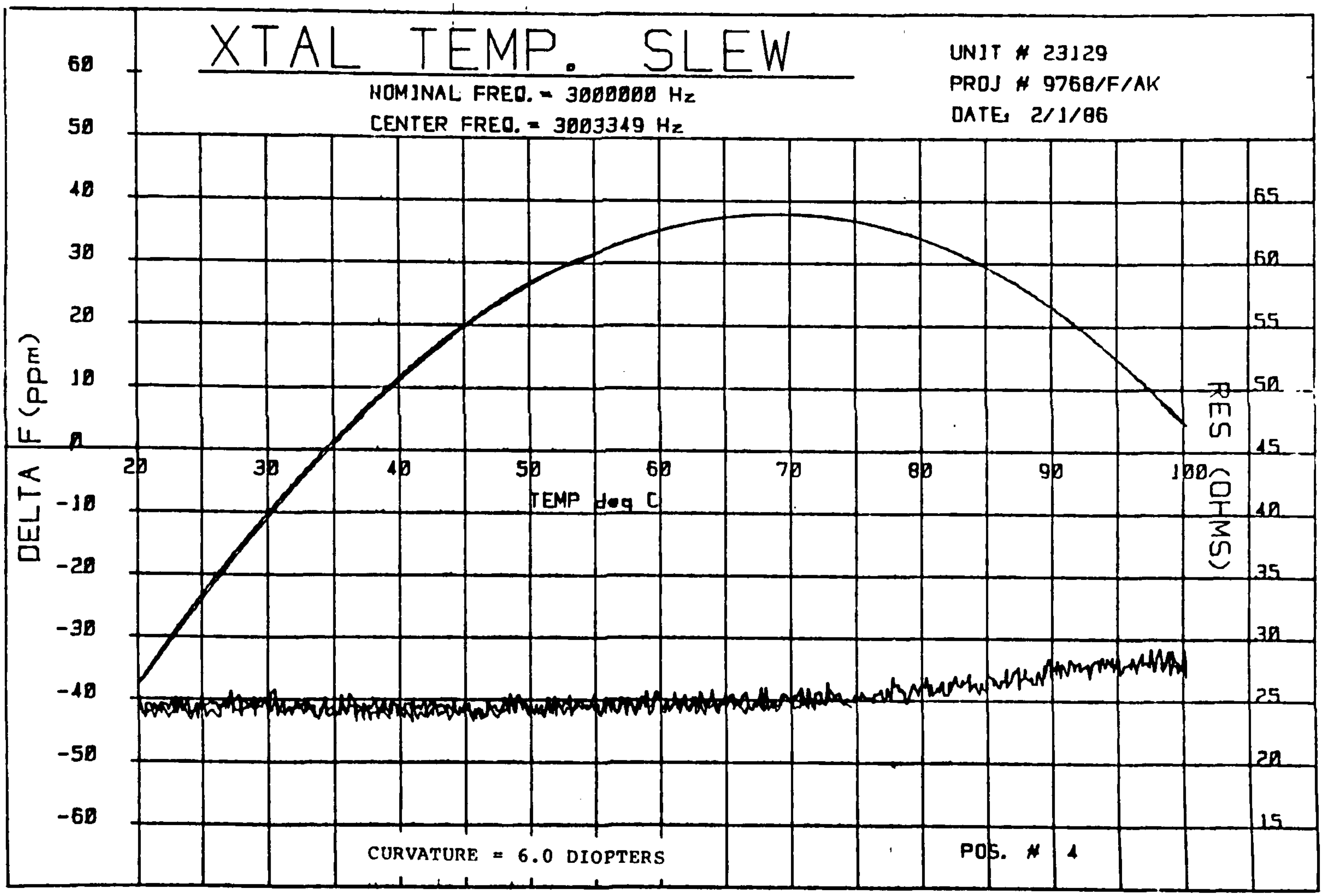
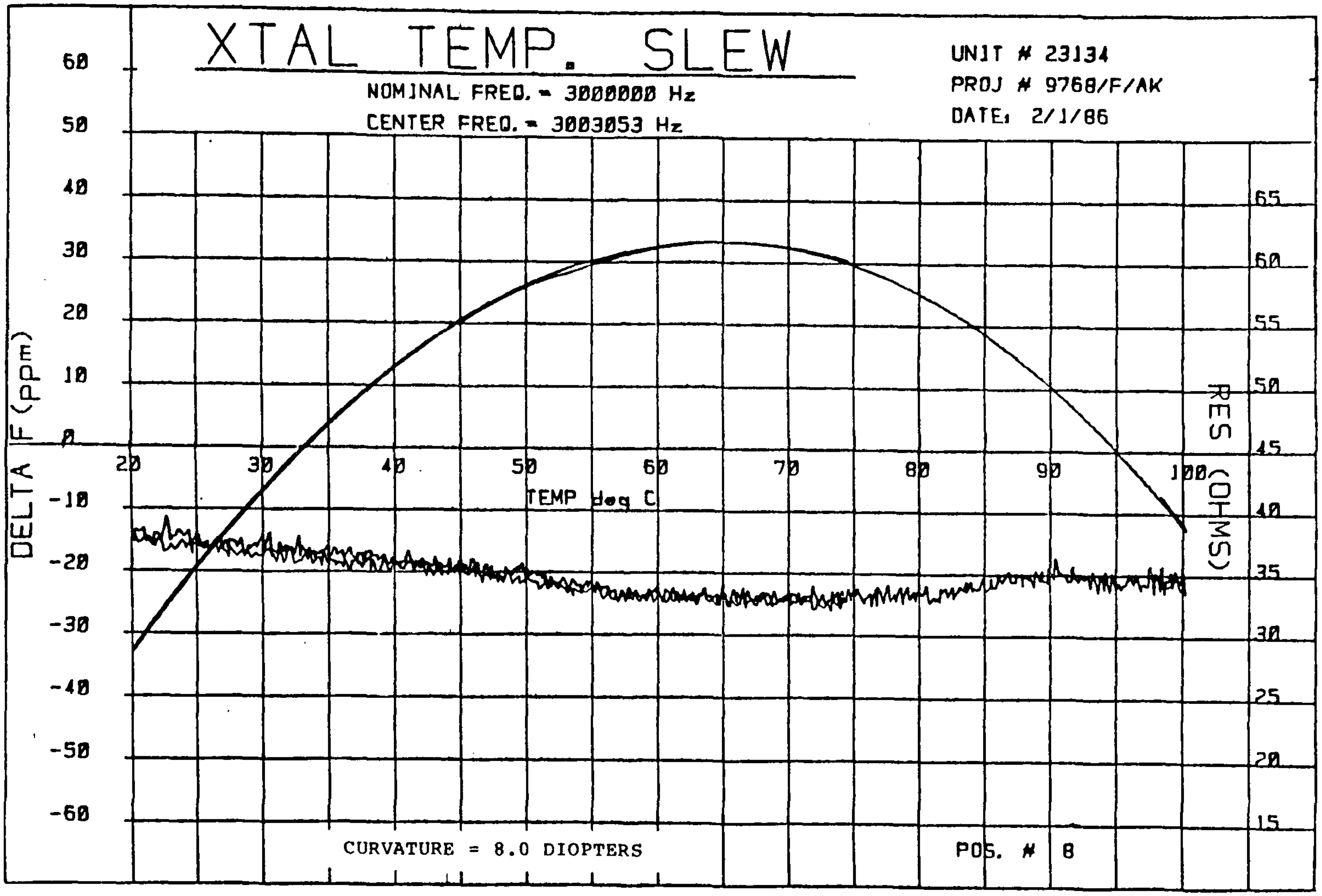
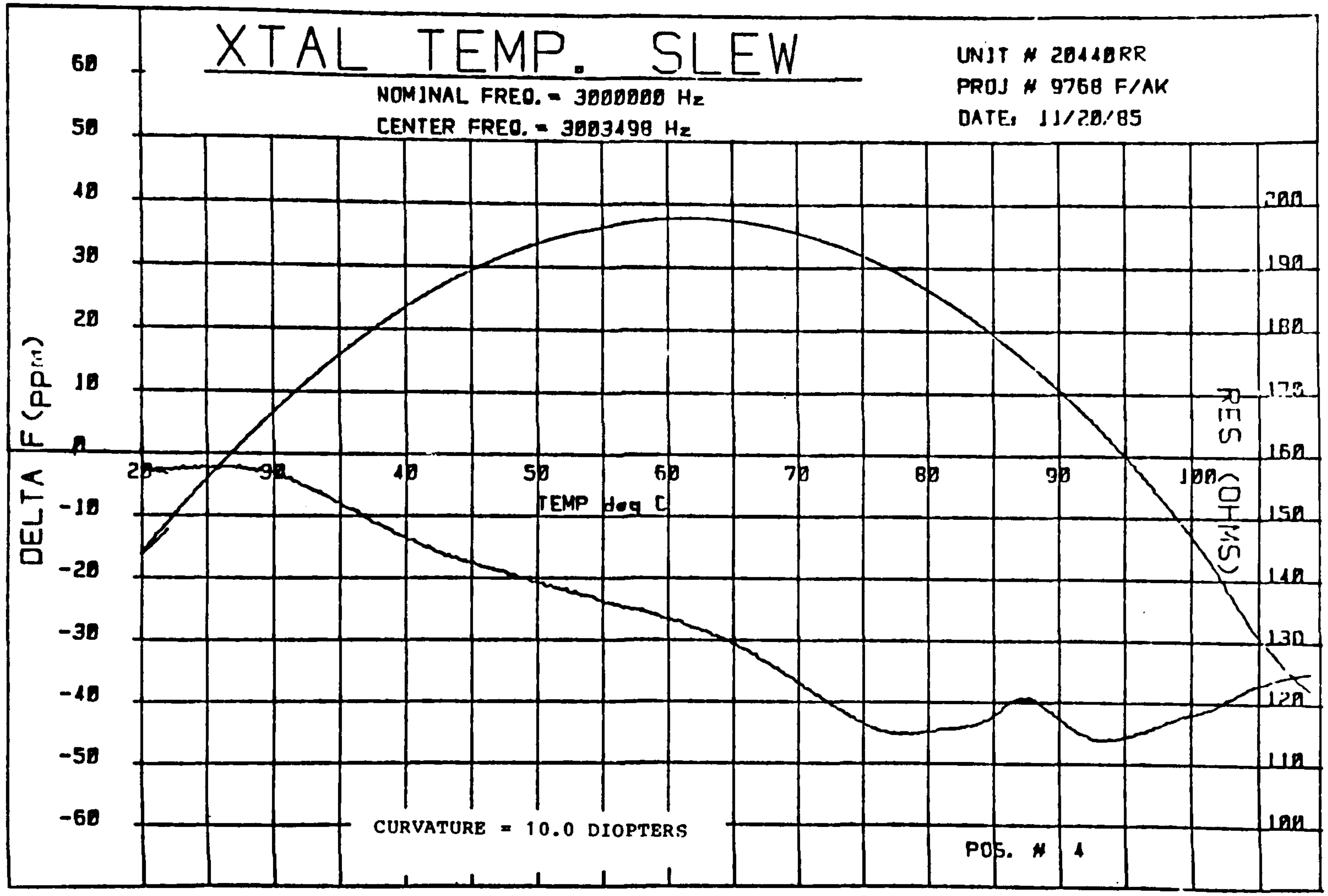

XTAL TEMP. SLEW
NOMINAL FREQ. = 3000000 Hz
CENTER FREQ. = 3003349 Hz
UNIT # 23129
PROJ # 9768/F/AK
DATE: 2/1/86
DELTA F (ppm)
TEMP deg C
RES (OHMS)
CURVATURE = 6.0 DIOPTERS
POS. # 4

FIGURE A-3



XTAL TEMP. SLEW
NOMINAL FREQ. = 3000000 Hz
CENTER FREQ. = 3003053 Hz
UNIT # 23134
PROJ # 9768/F/AK
DATE: 2/1/86
DELTA F (ppm)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
20
30
40
50
60
70
80
90
100
TEMP deg C
RES (OHMS)
65
60
55
50
45
40
35
30
25
20
15
CURVATURE = 8.0 DIOPTERS
POS. # 8

FIGURE A-4



XTAL TEMP. SLEW
NOMINAL FREQ. = 3000000 Hz
CENTER FREQ. = 3003498 Hz
UNIT # 20440RR
PROJ # 9768 F/AK
DATE: 11/20/85
DELTA F (ppm)
60
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
20
30
40
50
60
70
80
90
100
TEMP deg C
RES (OHMS)
200
190
180
170
160
150
140
130
120
110
100
CURVATURE = 10.0 DIOPTERS
POS. # 4

FIGURE A-5

FREQUENCY SWEEP
3.00/F/AK S/N 23129 $1F^2$ PB $\emptyset = 36.58^\circ$ $\theta = 26.00^\circ$
Curvature = 6.0 Diopter

FREQUENCY(HZ)	LEVEL(dB)	NOTE	RATIO
3003248	-3.97	'C' Mode Fundamental	
3141000	-27.1		
3248615	-7.02	'B' Mode Fundamental	$C_F/B_F = .924$
3283000	-25.1		
8756535	-21.2	'C' Mode Third O.T.	$C_3/B_3 = .916$
8867119	-18.68		$3F_F/F_3 = 1.020$
8905850	-31.56		
9026700	-19.6		
96737700	-41.6		
9676205	-37.0	'B' Mode, Third O.T.	
9689150	-48.5		
9805700	-53.0		
9864300	-50.0		$5F_F/F_5 = 1.026$
13836500	-13.5	'A' Mode	
14629740	-37.5	'C' Mode Fifth O.T.	$C_5/B_5 = .916$
15962311	-19.8	'B' Mode Fifth O.T.	$5F_F/F_5 = 1.026$
16109375	-46.7		
16196000	-24.2		

TABLE A-6

FREQUENCY SWEEP
3.00/F/AK S/N 23133 1F 2 P.B. $\emptyset = 36.58°$ $\theta = 26.00°$
Curvature = 8.0 Diopter

FREQUENCY(HZ)	LEVEL(dB)	NOTES	RATIOS
3003259	-5.44	'C' Mode Fundamental	
3160617	-41.2		
3270971	-7.42	'B' Mode Fundamental	$C_F/B_F = .9182$
3295250	-31.9		
3298000	-42.7		
8724576	-20.99	C Mode, Third O.T.	$C_3/B_3 = .9022$ $3F_F/F_3 = 1.032$
8858560	-19.86		
9047285	-24.5		
9168500	-33.1		
9639800	-44.3		
9659600	-47.3		
9668255	-46.0		
9669412	-40.1	'B' Mode, Third O.T.	
9678700	-52.0		
14411000	-50.8		
14519000	-52.1		
14575735	-48.7	'C' Mode, Fifth O.T.	$C_5/B_5 = .9166$
14687000	-55.0		$5F_F/F_5 = 1.030$
15672000	-57.2		
15901161	-24.8	'B' Mode, Fifth O.T.	
[illegible]0900	-40.6		

TABLE A-7

FREQUENCY SWEEP
3.00 F 'AK S/N 20440RR 1.0F ^{2} P.B. Ø = 36.58° θ = 26.00°
Curvature = 10.0 Diopter

FREQUENCY(HZ)	LEVEL(dB)	NOTES	RATIO
3003447	-16.31	'C' Mode Fundamental	
3180000	-48.0		
3239972	-39.0		C_F/B_F = .9112
3295897	-17.6	'B' Mode Fundamental	
3325938	-37.1		
3469040	-46.0		
8700212	-35.6	'C' Mode, Third O.T.	C_3/B_3 = .9015 $3F_F/F_3$ = 1.036
8862700	-37.4		
8896145	-38.1		
9082412	-47.2		
9317200	-50.2		
9650475	-50.3	'B' Mode, Third O.T.	
13778782	-37.1		
14480000	-54.0	'C' Mode, Fifth O.T.	C_5/B_5 = .9086
15935000	-51.8	'B' Mode, Fifth O.T.	$5F_F/F_5$ = 1.037
16240000	-53.0		

TABLE A-8

FREQUENCY SWEEP
4.00MHZ/F/AK S/N 23125 1F⁻ P.B. Ø = 36.58° θ = 26.00°
Curvature = 4.13 Diopter

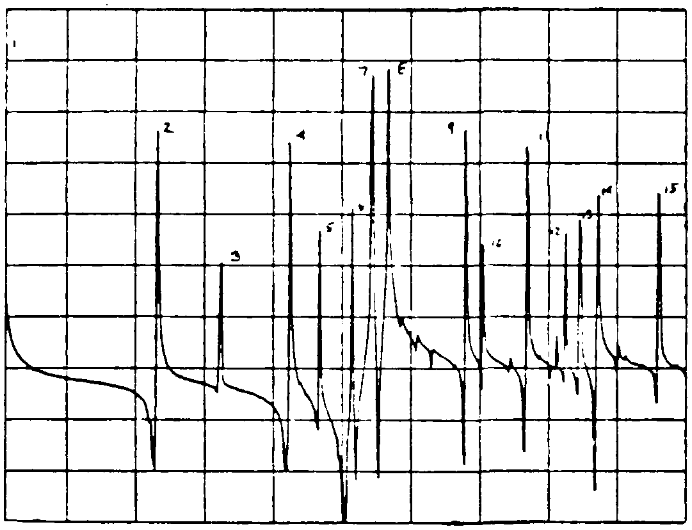
FREQUENCY(HZ)	LEVEL(dB)	NOTES	RATIOS
4003466	-2.78	'C' Mode Fundamental	C_F/B_F = .9148
4135720	-5.81		
4249518	-8.67		
4270759	-17.03		
4361805	-9.26		
4367663	-6.26		
4376120	-4.67	'B' Mode Fundamental	
11753493	-20.23	'C' Mode, Third O.T.	C_3/B_3 = .907
11987898	-18.69		3FF/F3 = 1.0219
12148668	-20.50		
12150602	-27.27		
12378034	-25.75		
12786029	-41.05		
12947587	-35.32	'B' Mode, Third O.T.	
12959950	-40.24		
19639789	-23.20	'C' Mode, Fifth O.T.	C_5/B_5 = .9158
21444624	-15.77	'B' Mode, Fifth O.T.	$5F_F/F_5$ = 1.0192
21586575	-33.23		
21664660	-21.73		
21730012	-26.08		

TABLE A-9

FREQUENCY SWEEP
4.00MHZ/PEAK S/N 23126 0.5F P.B. ϕ = 36.58° θ [illegible]
Curvature = 4.13 Diopter

FREQUENCY(HZ)	LEVEL(dB)	NOTES	RATIOS
4009233	-3.32	C Mode Fundamental	C_F/B_F = .9142
4141413	-6.27		
4373516	-8.57		
4385329	-3.23	'B' Mode Fundamental	
11771949	-20.17	'C' Mode, Third O.T.	C_3/B_3 = .9053 $3F_F/F_3$ = 1.0217
11863279	-19.50		
11914457	-25.50		
12006172	-18.91		
12131465	-27.6		
12166705	-21.8		
12168700	-27.54		
12966461	-32.9		
12978300	-35.4		
12987005	-33.9		
12995569	-30.85		
13003026	-23.96	'B' Mode, Third O.T.	
13032632	-33.4		
19669108	-23.33	'C' Mode, Fifth O.T.	C_5/B_5 = .9149
21499297	-15.75	'B' Mode, Fifth O.T.	$5F_F/F_5$ = 1.0192
21640945	-25.62		
21718613	-20.17		
21783812	-28.73		

TABLE A-10



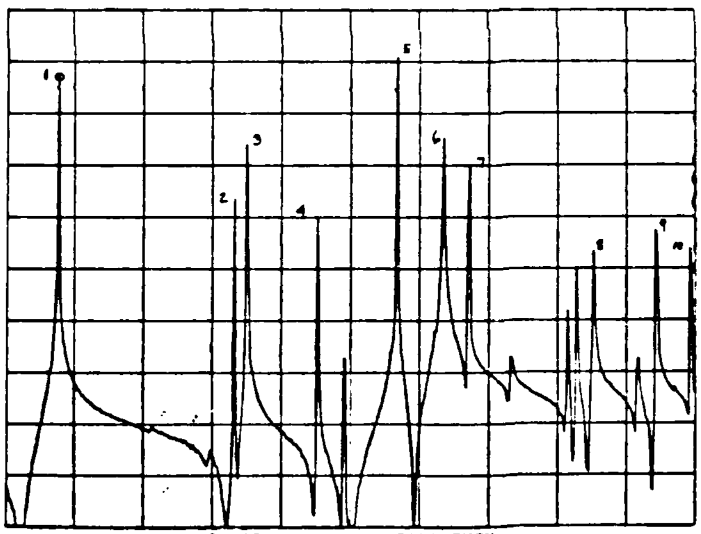
3.000MHz - START FREQUENCY
3.500MHz - STOP FREQUENCY

NO	FREQ(Hz)	dB LEVEL
1	3002966.500	-3.281
2	3116574.500	-16.241
3	3161890.725	-26.078
4	3212600.500	-18.315
5	3233715.750	-42.524
6	3257733.000	-21.908
7	3271902.500	-8.843
8	3264080.500	-7.981
9	3340323.000	-17.136
10	3352505.500	-45.820
11	3384812.750	-26.798
12	3412693.000	-43.304
13	3423094.000	-41.074
14	3436285.000	-36.221
15	3480577.250	-33.729

NOTES

1. NUMBERS 1 THRU 15 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 4.125 DIOPTER.
4. CRYSTAL S/N 23125

Figure A-11. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 4.13 Diopter



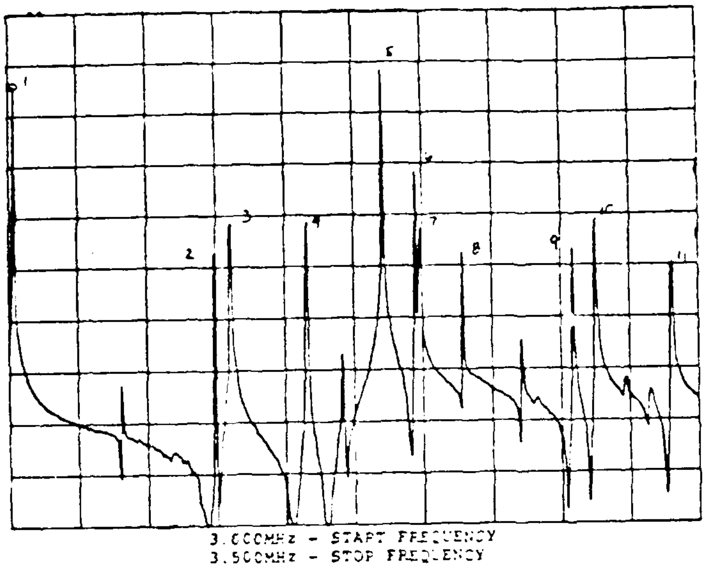
3.965MHz - START FREQUENCY
3.465MHz - STOP FREQUENCY

NO	FREQ(Hz)	dB LEVEL
1	3003262.875	-3.878
2	3131475.500	-30.658
3	3140408.000	-28.137
4	3191723.000	-40.141
5	3248632.250	-6.958
6	3282435.750	-24.851
7	3300644.250	-22.466
8	3391136.000	-46.735
9	3436751.750	-42.760
10	3461824.000	-45.261

NOTES

1. NUMBERS 1 THRU 10 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 6.0 DIOPTER
4. CRYSTAL S/N 23129

Figure A-12. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 6.0 Diopter

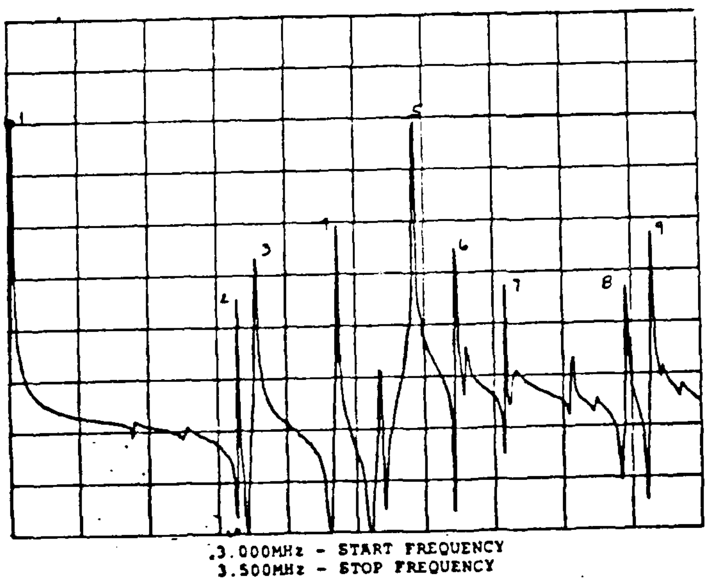


NO	FREQ(Hz)	dB LEVEL
1	3003275.500	-5.367
2	3149273.500	-36.982
3	3160621.000	-41.249
4	3215713.000	-41.268
5	3270956.250	-7.256
6	3295106.250	-31.261
7	3298213.000	-42.349
8	3328753.750	-47.233
9	3408713.500	-46.823
10	3425347.500	-4[illegible].634
11	3480642.500	-49.839

NOTES

1. NUMBERS 1 THRU 11 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 8.0 DIOPTER.
4. CRYSTAL S/N 23133

Figure A-13. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 8.0 Diopter

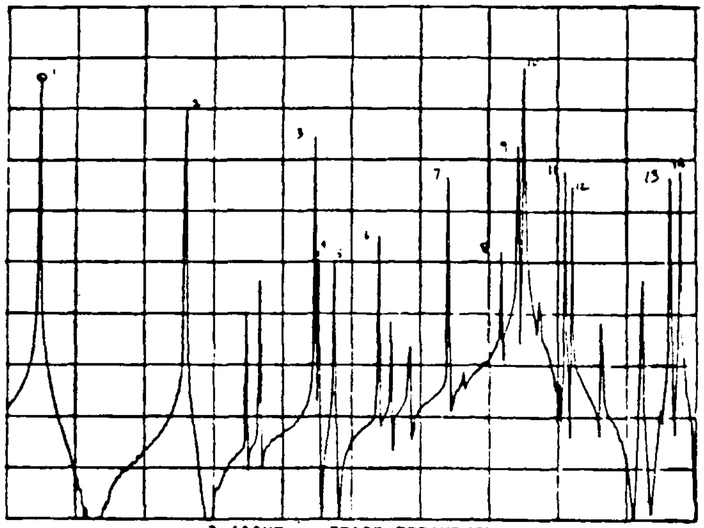


NO	FREQ(Hz)	dB LEVEL
1	3002985.750	-17.972
2	3165254.250	-53.141
3	3178680.250	-46.560
4	3237505.750	-40.350
5	3293101.750	-20.739
6	3322970.500	-45.093
7	3358419.750	-52.828
8	3446561.000	-53.149
9	3465055.500	-42.834

NOTES

1. NUMBERS 1 THRU 9 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF LEVEL -0.000dB
3. 3.0MHz/F/AK AT 10.0 DIOPTER.
4. CRYSTAL S/N 20431R

Figure A-14. Frequency Responses On The Fundamental For A 3.0 MHz/F/AK Resonator At 10.0 Diopter



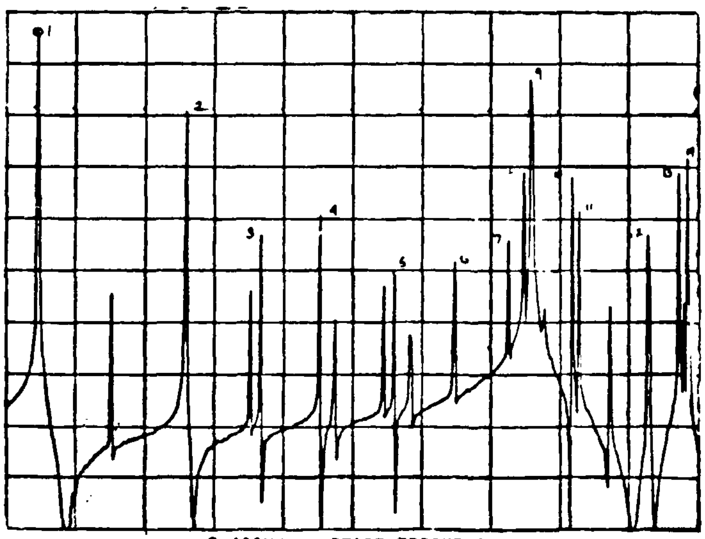
NO	FREQ (Hz)	dB LEVEL
1	3428006.250	-3.478
2	3555326.000	-9.[illegible]
3	3668531.750	-15.797
4	3671496.000	-29.187
5	3689589.750	-49.689
6	3723444.750	-36.594
7	3784520.000	-25.456
8	3830947.650	-32.399
9	3845024.000	-27.149
10	3850393.500	-11.206
11	3885665.250	-31.885
12	3891791.500	-29.182
13	3978086.000	-31.791
14	3985829.500	-31.950

NOTES:

1. NUMBERS 1 THRU 14 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2 REF. LEVEL -0.000dB
3 10.0MHz/3/AK AT 4.125 DIOPTER.
4 CRYSTAL S/N 20457R
5 .265" DIAMETER ELECTRODE

3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

Figure A-15. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 4.125 Diopter Plated With A .265" Diameter Electrode



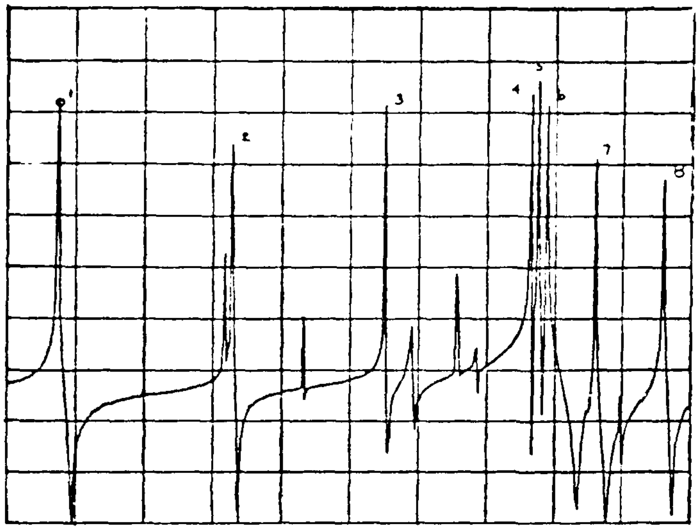
NO	FREQ (Hz)	dB LEVEL
1	3427715.000	-3.973
2	3555594.250	-15.995
3	3620195.250	-42.431
4	3671601.000	-21.110
5	3736369.250	-49.950
6	3787882.750	-33.723
7	3835389.250	-31.178
8	3848436.500	-30.254
9	3855200.750	-12.432
10	3890792.500	-27.713
11	3896094.750	-36.623
12	3957204.250	-42.448
13	3983860.000	-22.753
14	3999461.500	-23.852

NOTES:

1. NUMBERS 1 THRU 14 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2 REF. LEVEL -0.000dB
3 10.0MHz/3/AK AT 4.125 DIOPTER.
4 CRYSTAL S/N 20459R
5 .221" DIAMETER ELECTRODE

3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

Figure A-16. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 4.125 Diopter Plated With A .221" Diameter Electrode



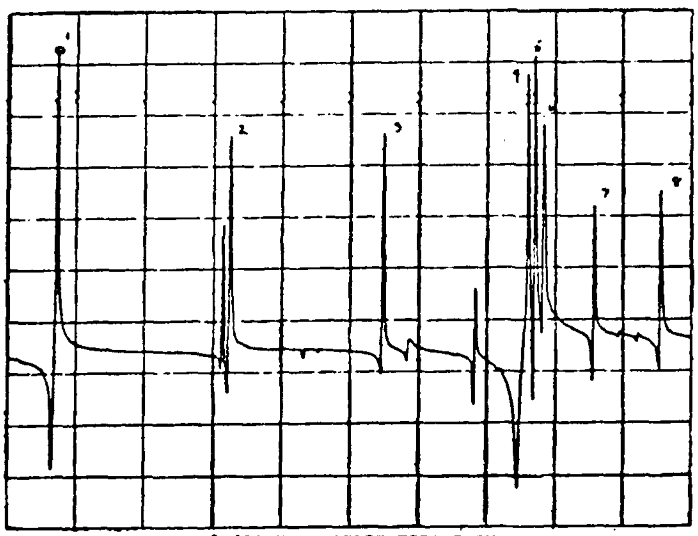
NO.	FREQ(Hz)	dB LEVEL
1	3444275.250	-3.269
2	3597090.250	-25.072
3	3729845.500	-14.014
4	3858367.250	-15.965
5	3864836.250	-9.400
6	3872884.250	-18.401
7	3916194.750	-28.560
8.	3976137.525	-31.903

NOTES:

1. NUMBERS 1 THRU 8 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2 REF. LEVEL -0.000dB
3 10.0MHz/3/AK AT 6.0 DIOPTER.
4 CRYSTAL S/N 20448R
5 .265" DIAMETER ELECTRODE

3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

Figure A-17. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 6.0 Diopter Plated With A .265" Diameter Electrode



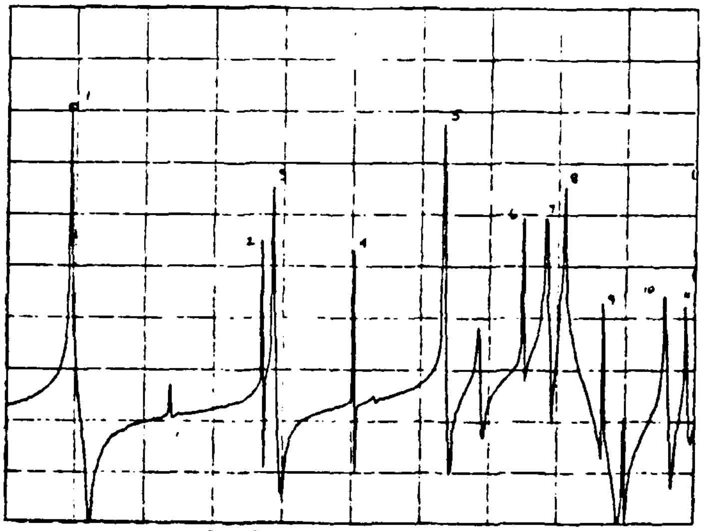
NO	FREQ(Hz)	dB LEVEL
1	3443770.250	-3.889
2	3595500.500	-21.457
3	3729142.000	-18.071
4	3856386.250	-9.740
5	3862234.500	-5.872
6	3870104.500	-20.352
7	3914062.500	-37.875
8	3973399.000	-34.807

NOTES:

1. NUMBERS 1 THRU 8 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2 REF. LEVEL -0.000dB
3 10.0MHz/3/AK AT 6.0 DIOPTER.
4 CRYSTAL S/N 20450R
5 .221" DIAMETER ELECTRODE

3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

Figure A-18. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 6.0 Diopter Plated With A .221" Diameter Electrode



3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

NO	FREQ(Hz)	dB LEVEL
1	3456012.000	-4.088
2	3622682.750	-37.202
3	3631330.250	-34.678
4	3701028.250	-46.744
5	3780198.500	-16.684
6	3849718.000	-38.586
7	3870074.750	-40.278
8	3885644.000	-34.586
9	3920177.250	-56.172
10	3974590.000	-55.857
11	3992766.750	-57.685

NOTES:

1. NUMBERS 1 THRU 11 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 8.0 DIOPTER.
4. CRYSTAL S/N 20452R
5. .265" DIAMETER ELECTRODE

Figure A-19. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 8.0 Diopter Plated With A .265" Diameter Electrode

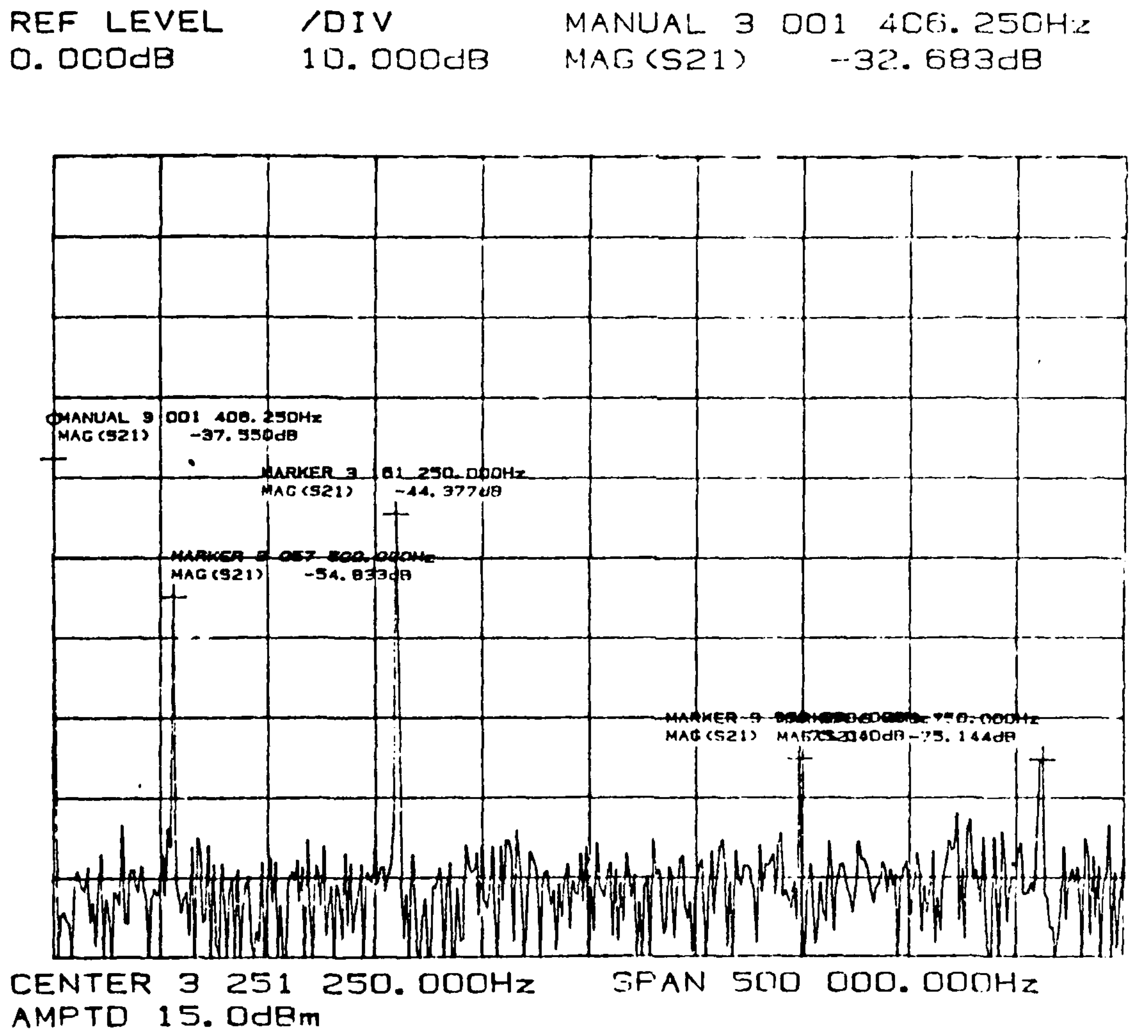
3.400MHz - START FREQUENCY
4.000MHz - STOP FREQUENCY

NO	FREQ(Hz)	dB LEVEL
1	3457390.000	-5.319
2	3624423.750	-24.533
3	3632988.250	-33.395
4	3782579.000	-19.757
5	3852129.500	-46.140
6	3872562.250	-39.605
7	3888541.500	-32.717

NOTES:

1. NUMBERS 1 THRU 7 RESPECTIVELY CORRESPOND TO EACH FREQUENCY RESPONSE IN SPUR PLOT.
2. REF. LEVEL -0.000dB
3. 10.0MHz/3/AK AT 8.0 DIOPTER.
4. CRYSTAL S/N 20457R
5. .221" DIAMETER ELECTRODE

Figure A-20. Frequency Responses On The Fundamental For A 10.0 MHz/3/AK Resonator At 8.0 Diopter Plated With A .221" Diameter Electrode



AK LFR #12

3.001401	-23.8
3.057592	-47.3
3.161812	-40.8
3.350000	-71.7
3.463750	-73.0

Fundamental Mode
Frequency Response
on an AK-LFR
Gap = 0.075
$\vec{\omega}$ = 255°

FIGURE A-21

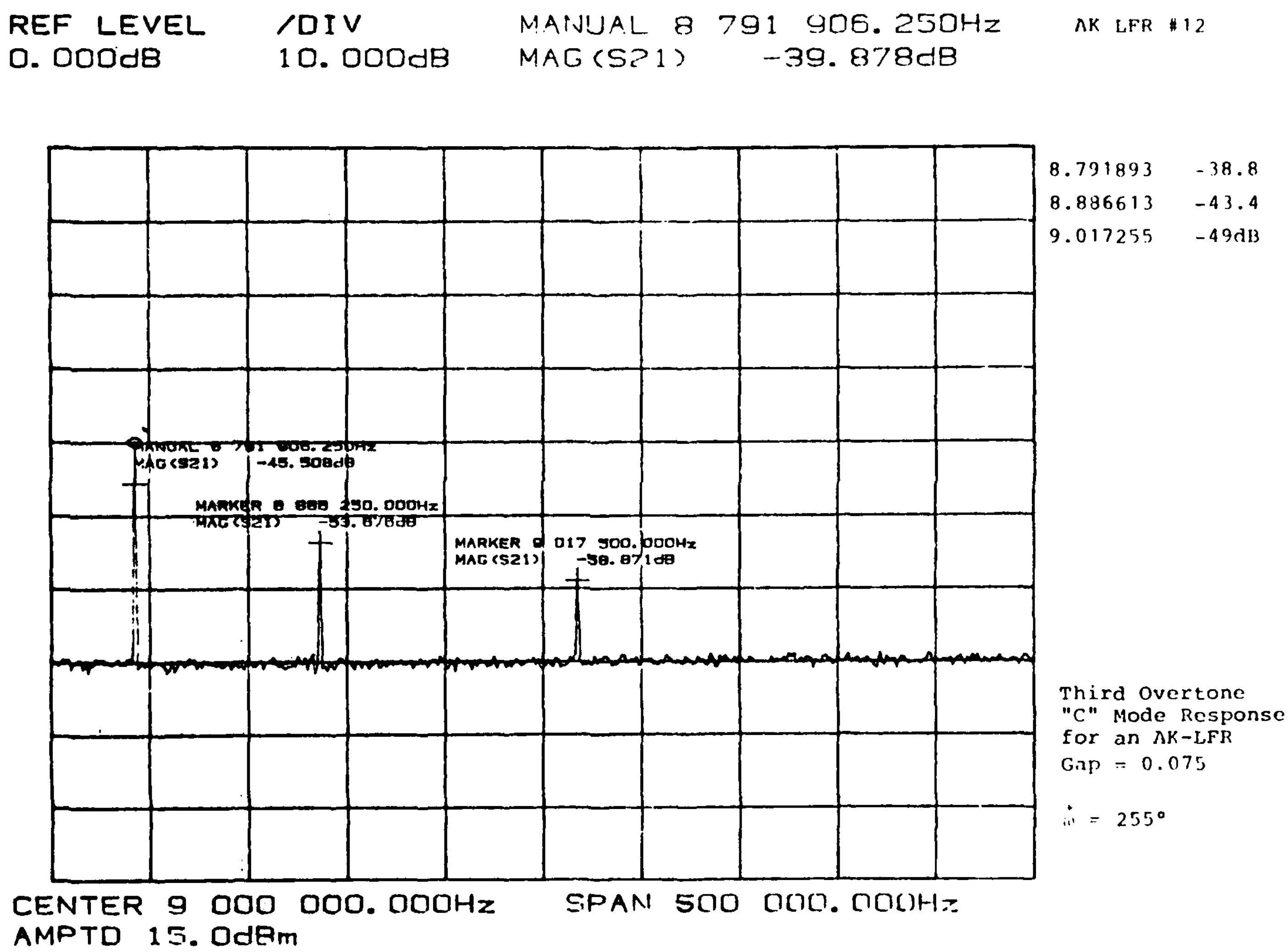

REF LEVEL /DIV MANUAL 8 791 906.250Hz AK LFR #12
0.000dB 10.000dB MAG(S21) -39.878dB
8.791893 -38.8
8.886613 -43.4
9.017255 -49dB
MAG(S21) -45.508dB
MARKER 9 017 500.000Hz
MAG(S21) -58.871dB
Third Overtone
"C" Mode Response
for an AK-LFR
Gap = 0.075
= 255°
CENTER 9 000 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FIGURE A-22

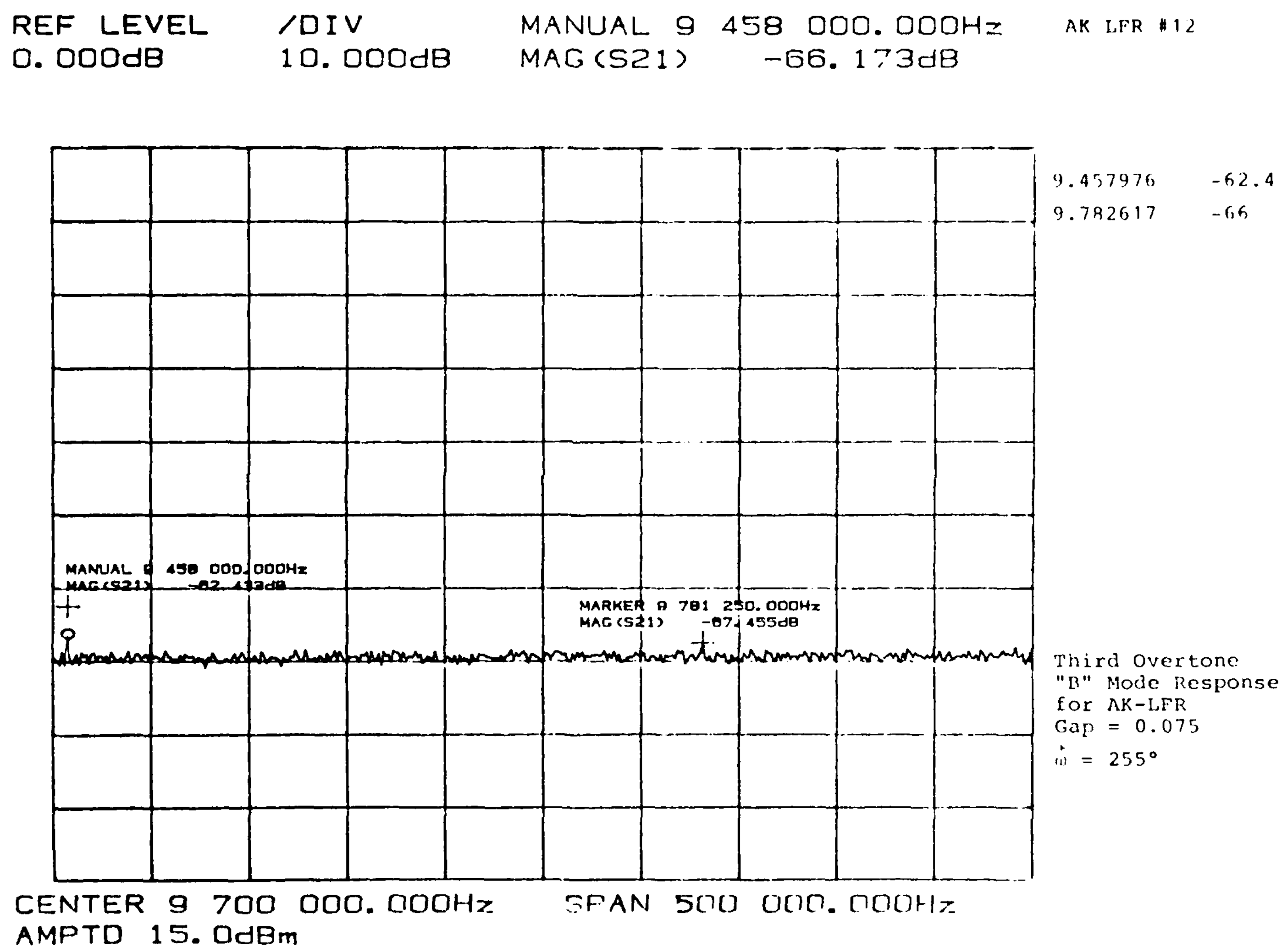
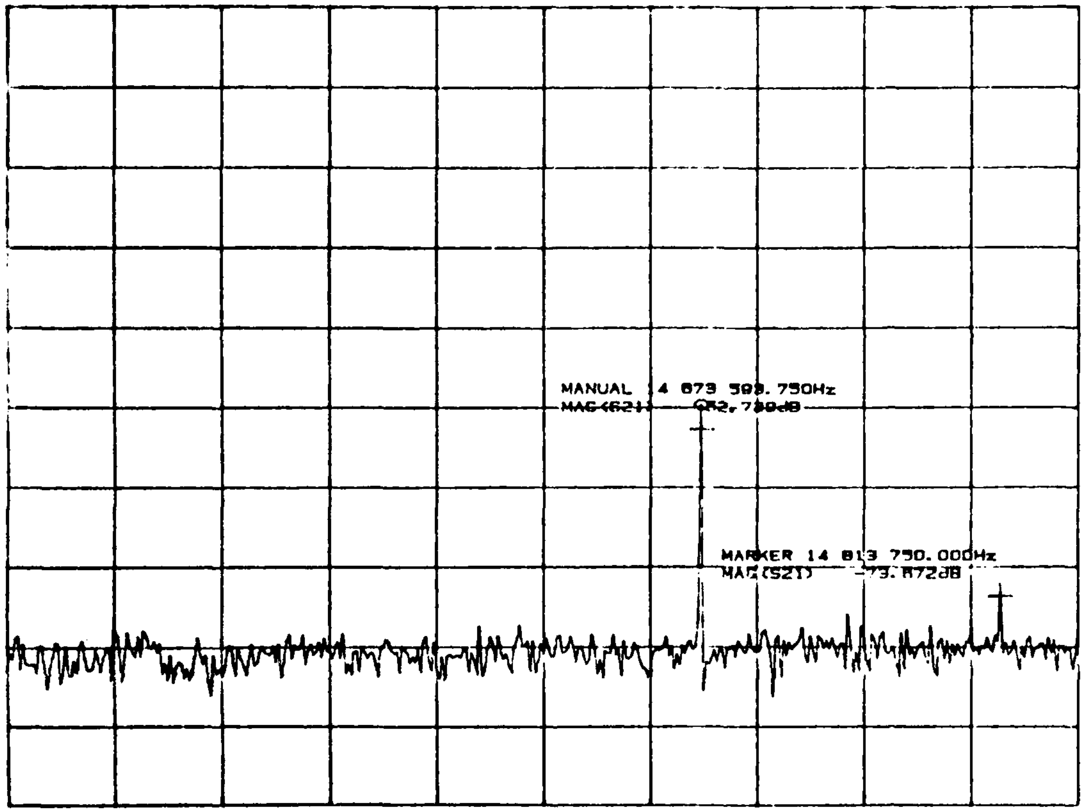

REF LEVEL /DIV MANUAL 9 458 000.000Hz
0.000dB 10.000dB MAG(S21) -66.173dB
AK LFR #12
9.457976 -62.4
9.782617 -66
MANUAL 9 458 000.000Hz
MARKER 9 781 250.000Hz
Third Overtone
"B" Mode Response
for AK-LFR
Gap = 0.075
ω = 255°
CENTER 9 700 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FIGURE A-23

REF LEVEL /DIV MANUAL 14 673 593.750Hz AK LFR #12
0.000dB 10.000dB MAG(S21) -49.676dB



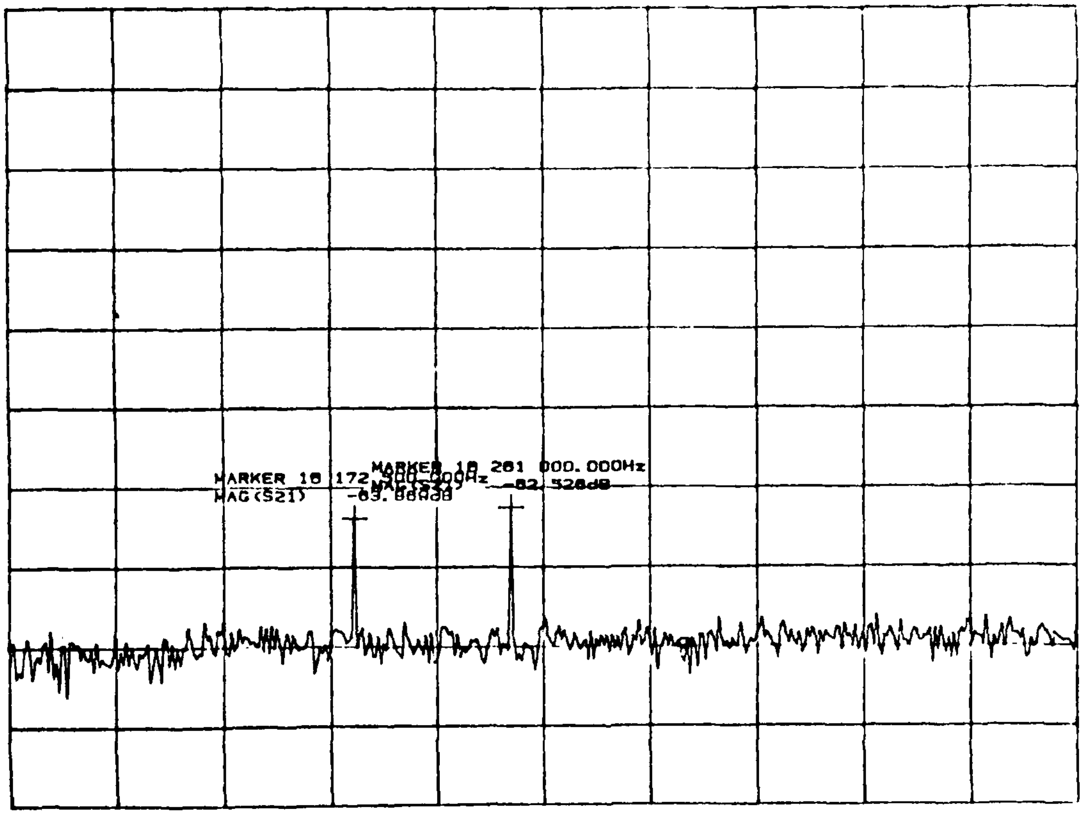
14.673577 -48.3
14.813 -73

Fifth Overtone
"C" Mode for an
AK-LFR
Gap = 0.075
$\vec{\omega}$ = 255°

CENTER 14 600 000.000Hz SPAN 500 000.000Hz
AMPTD 15.0dBm

FIGURE A-24

REF LEVEL /DIV MANUAL 16 358 312.500Hz AK LFR# 12
0.000dB 10.000dB MAG(S21) -79.801dB



16.171864 -62.4
16.271654 -60.8

Fifth Overtone
"B" Mode for an
AK-LFR
Gap = 0.075
$\vec{\omega}$ = 255°

CENTER 16 279 000.000Hz SPAN 600 000.000Hz
AMPTD 15.0dBm

FIGURE A-25

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RADC plans and executes research, development, test and selected acquisition programs in support of Command, Control, Communications and Intelligence (C^3I) activities. Technical and engineering support within areas of competence is provided to ESD Program Offices (POs) and other ESD elements to perform effective acquisition of C^3I systems. The areas of technical competence include communications, command and control, battle management, information processing, surveillance sensors, intelligence data collection and handling, solid state sciences, electromagnetics, and propagation, and electronic, maintainability, and compatibility.